Temporal and spatial judgments of occluded motion:

Unimodal and crossmodal influences

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to be defended in public on Tuesday, December 18, 2018
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by

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Born on November 22, 1985
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Introduction

In daily life we are surrounded by all kinds of moving objects. For example, one may think of a traffic scene in which you want to cross a street. We then need to continuously estimate and predict the position of objects such as bicycles and cars to safely get to the other side of the road. Or consider a situation when trying to catch a ball, or judging when to step on a moving escalator. Many of the (moving) objects in scenes like these might not be visible all of time, simply because other objects temporarily occlude them. Yet, we are able to make rather accurate estimations where an occluded moving object is at any certain moment. This thesis focuses on the perceived duration of events that comprise moving objects in situations when they are visible and when they are distracted from sight, as well as on the inferred position of objects when they are occluded. In addition, we investigated perceived duration of such events not only based on visual information, but also cross-modally by investigating the influence of auditory stimuli on the perceived duration.

The central question in this thesis is how we judge the timing of visual motion, in particular when objects become 'invisible', e.g., when a moving object traverses behind other objects in a scene. To do this, we manipulated various factors that were hypothesized to influence the expected reappearance of the temporarily occluded objects. Time is an integral component of human lives. We can sense, estimate or relate time to many aspects of events we encounter. Not only can the perceived duration of past events affect our experiences, but the judged duration of an ongoing event can do also. For example, when you know how long it takes to drive from your home to your office, you can estimate the time of arrival. Not only time estimations in relatively large units (e.g., hours) are important, but time estimations in smaller units (e.g., seconds) are also important, especially in the case of a visual motion (we could get hit by a moving vehicle if we miscalculate the time it takes the vehicle to reach us).

Next, I first review some earlier research on time perception in the visual and the auditory modality, followed by cross-modal effects of spatiotemporal characteristics of auditory and visual stimuli that influence the spatial and temporal judgments of an event. After that, I will review a few models on time perception that are related to the chapters in this thesis and additionally describe a few methods to study time estimation.

Influencing time judgments of moving objects

The tunnel effect, amodal movement & motion extrapolation

Many characteristics (e.g., number, speed) of moving objects influence perceived time (Brown, 1995). For example, faster movements have been shown to lead to lengthening of perceived time as compared to slower movements (Brown, 1995). Still, when judging real life situations we have to deal not only with visible moving objects, but also with objects that temporarily disappear behind other objects. In laboratory settings this phenomenon has been investigated by means of the so-called *Tunnel Effect* (Burke, 1952; Michotte, 1950); a moving object disappears behind an occluder and after some time reappears at the other side of that occluder (Figure 1.1). The spatiotemporal continuity is dominant over the surface features of a moving object, even when the features (e.g., color, shape) of the reappeared object are different from the

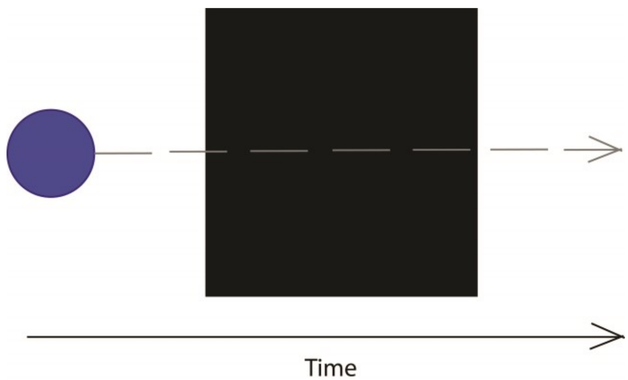

Figure 1.1. The tunnel effect. A blue moving disk disappears behind a black occluder and then it reappears after the occlusion.

object that disappeared (Flombaum, Kundey, Santos, & Scholl, 2004; Flombaum & Scholl, 2006; Flombaum, Scholl, & Santos, 2009; Yi et al., 2008). That is, if the occluded moving object reappears within a specific time window after disappearance, the reappeared object is likely to be perceived as the same object.

In each of the following chapters, experiments are performed on moving disks that at a certain point disappear behind an occluder, similar to the one shown in Figure 1.1. We will refer to an object's motion during occlusion with the term *amodal movement*. When a moving object disappears behind an occluder, observers tentatively estimate the future location of that object at a specific moment in time, which is generally called *motion extrapolation* (e.g., DeLucia & Liddell, 1998; Makin, Poliakoff, Chen, & Stewart, 2008). Previous research showed that many factors influence motion extrapolation, e.g., the speed and size of moving objects affected the judged time that the objects when temporarily occluded would move to reach a specific location (Sokolov, Ehrenstein, Pavlova, & Cavonius, 1997; Tresilian, Oliver, & Carroll, 2003; Tresilian & Plooy, 2006). For example, a relatively large object was judged to take a longer duration to move to a specific location than a relatively small object (Sokolov et al., 1997). In Chapter 2 we compare time durations in motion trajectories in which occlusion is involved (i.e., using the tunnel effect) with similar trajectories, but without occlusion. In Chapters 3 and 4, we study the influence of auditory input on perceived durations and extrapolated distances. That is, we are not only interested in spatiotemporal perception of a visual movement, but also in the effect of auditory input on spatiotemporal perception. Before zooming in on specific auditory influences on timing of visual events we first briefly review some phenomena regarding the perception of auditory events.

Time perception of auditory sequences

Many previous studies revealed that auditory stimuli (i.e., sound sequences) can affect perceived duration of an event (Foley, Michaluk, & Thomas, 2004; Ihle & Wilsoncroft, 1983; Penton-Voak, Edwards, Percival, &

Wearden, 1996; Wearden, Norton, Martin, & Montford-Bebb, 2007). For example, Ihle and Wilsoncroft (1983) found that time intervals filled with auditory stimuli were judged to last longer than non-filled intervals, even when the actual duration of both time intervals were the same. A recent study that used verbal reports and temporal generalization (i.e., comparing the test duration to a standard duration) revealed that time intervals filled with auditory stimuli were perceived as approximately 55%-65% longer than non-filled intervals (Wearden et al., 2007). These experimental results are examples of the *filled-duration illusion* that states that a filled-duration is more arousing than a non-filled (i.e., silent) duration (Wearden et al., 2007).

An important property of auditory sequences is rhythm. Perception of rhythm is involved in auditory streams such as speech (Magne, Jordan, & Gordon, 2016) or music (Hasuo, Nakajima, Wakasugi, & Fujioka, 2015; Large, Herrera, & Velasco, 2015). Speed of rhythm is defined as duration divided by the number of sound onsets (e.g., Handel, 1993; McAdams & Drake, 2002; Patel, 2008). It has been shown that the speed of rhythm can influence perceived duration (Foley et al., 2004; Penton-Voak et al., 1996). For example, when participants listened to a relatively fast training sequence followed by a relatively slow test sequence, they judged durations to be longer than they actually were, and vice versa (Foley et al., 2004). In the experiments of Penton-Voak et al (1996)'s study, using various time estimation methods, five-second sequences of clicks presented at a rate of 5 Hz or 25 Hz both lengthened subjective perceived durations as compared to five seconds of silence. Vroon (1970) also showed that durations that were filled with a higher number of sound onsets (i.e., fast rhythm) were judged to last longer than durations that were filled with a fewer number of sound onsets (i.e., slow rhythm). All of the phenomena mentioned, clearly showed that auditory rhythmic sequences can influence the perceived time of auditory events, and these studies raise the question whether rhythmic sounds can also affect the perceived time of visual events. That is, we question whether there are cross-modal influences with regard to judged time durations.

Cross-modal influences

Previous studies have shown that vision is usually dominant over audition in the spatial domain while audition is dominant over vision in the temporal domain (e.g., Battaglia, Jacobs, & Aslin, 2003; Burr, Banks, & Morrone, 2009; Getzmann, 2007; Repp & Penel, 2002; Witten & Knudsen, 2005). However, recent studies revealed that in the spatial domain audition can be dominant over vision in some conditions (Grassi & Casco, 2010; Shams, Ma, & Beierholm, 2005). For example, a sound that was presented 200 ms before two moving objects overlap led participants to perceive the two moving objects collide with each other, more often than the no-sound condition (Grassi & Casco, 2010). Moreover, participants perceived bouncing more frequently when a congruent sound (e.g., a sound of a billiard ball hitting a second ball) was presented as compared to when an incongruent sound (e.g., a sound of water dropping into water) was presented (Grassi & Casco, 2010). In another famous audio-visual demonstration, it appeared that the number of sounds influenced the number of visual flashes participants reported to perceive (Shams, Kamitani, & Shimojo, 2000, 2002). All of these findings reveal clear cross-modal influences from the auditory modality to the visual modality.

In this thesis, we focus on auditory influences on perceived durations (Chapter 3) and perceived distance (Chapter 4) of amodal movements. Perceived duration and distance are two aspects that are closely related, and can influence each other (Cohen, Hansel, & Sylvester, 1953; Grondin & Plourde, 2007; Helson, 1930; Maij, Brenner, & Smeets, 2009; Price-Williams, 1954; Roussel, Grondin, & Killeen, 2009). For example, a longer duration between two consecutive sounds, presented at two spatially different locations (one after the other), led to a longer perceived distance between these two consecutive sounds as compared to a shorter duration (Sarrazin, Giraudo, & Pittenger, 2007; Shigeno, 1986, 1993). Similarly, a longer duration between two tactile stimuli led participants to judge the distance between these two stimuli to be longer than it actually was, and vice versa (Helson, 1930). This phenomenon in which the duration between stimuli also influences the perceived spatial distance between those stimuli is called the *'Tau effect'* (Helson, 1930) (Figure 1.2). Not only can duration influence perceived distance, but, as also evidenced in the example above where sounds originated from different locations, distance can also influence perceived duration and this phenomenon is called *'Kappa effect'* (Cohen et al., 1953; Price-Williams, 1954) (Figure 1.2). For example,

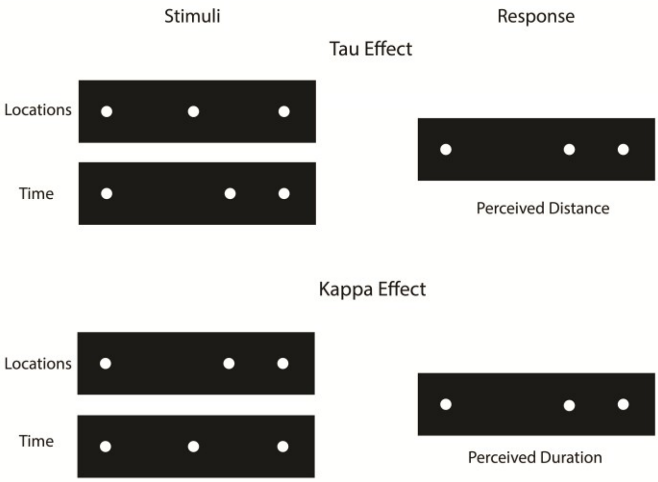

Figure 1.2. Schematic diagrams of the Tau and Kappa effects (adapted from Sarrazin, Giraudo & Pittenger, 2007). In the Tau effect, there are three stimuli presented at three different locations (top left panel). The timing of the presentation of these three stimuli (panel on second row) is such that the second (i.e., middle) stimulus is not presented midway between the presentation of the first and third stimuli, but rather such that it is presented closer in time to the third (i.e., final) stimulus. The result (panel on the top right side) is that the *perceived location* of the middle stimulus is closer to the third (i.e., final) stimulus, and *perceived distance* between the first and the middle stimuli is longer than the one between the middle and the third stimuli. In the Kappa effect, there are three stimuli presented at three different locations (bottom left panel). The timing of the presentation of these three stimuli (panel on last row) is such that the second (i.e., middle) stimulus is presented midway between the presentation of the first and third stimuli. The result (panel on the bottom right side) is that the *perceived duration* between the first and the middle stimuli is longer than the one between the middle and the third stimuli.

Price-Williams (1954) found that the duration between two flashed lights was perceived to last longer when the physical distance between them was relatively large, and vice versa. Moreover, when the distances between two successive sounds were varied, perceived durations between two successive sounds also changed, even when all the durations between the sounds (i.e., the inter sound intervals) were actually equal (Grondin & Plourde, 2007).

Perceived duration and distance can also be influenced by stimuli in a different modality. That is, recently, audiovisual Tau and Kappa effects have been reported in the context of visual apparent motion (Kawabe, Miura, & Yamada, 2008; Kawabe et al., 2010). For example, in Kawabe et al. (2008)'s study, three flashes at three different locations were accompanied by three sounds. While the onsets of the first and third sounds were identical to the first and third flashes respectively, the onset of the second (i.e., middle) sound was not. That is, the onset of the second sound could be just prior or just after the onset of the second flash. Participants perceived a shorter distance between two consecutive flashes (e.g., between the first and second flash) when the duration between two consecutive sounds (e.g., between the first and second sound) was relatively short, and vice versa (Kawabe et al., 2008). In addition, audiovisual integration has been shown to also affect motion extrapolation of visual movements (DeLucia, Preddy, & Oberfeld, 2016; Hofbauer et al., 2004; Wuerger, Meyer, Hofbauer, Zetzsche, & Schill, 2010). For example, Time To Contact (TTC) judgments of serial presentations of both clicks and flashes (i.e., bimodal) were more precise than TTC judgments of either serial presentations of clicks or flashes (Hofbauer et al., 2004; Wuerger et al., 2010). Moreover, when both visual and auditory information were presented, TTC judgments for an approaching object appeared to rely more on visual information than on auditory information (DeLucia et al., 2016). Note that many previous TTC studies focused on approaching moving objects in which the objects gradually increased their sizes as they moved along their trajectories (DeLucia, 2004; DeLucia et al., 2016; Iwasaki & Yamakawa, 2006; Zhou et al., 2007), and also focused on actually moving sound sources (Hofbauer et al., 2004; Wuerger et al., 2010). In contrast, the experiments in our studies focus more on spatiotemporal judgments of amodal movements without further visual cues and sounds without spatial cues. As will be clear this allows to better focus on particular properties of the auditory rhythm to test its influence on the amodal movements.

Models on time perception

Internal clock model

A well-known time perception model is the *internal clock model* (Treisman, 1963) (Figure 1.3). This model is in line with many research findings

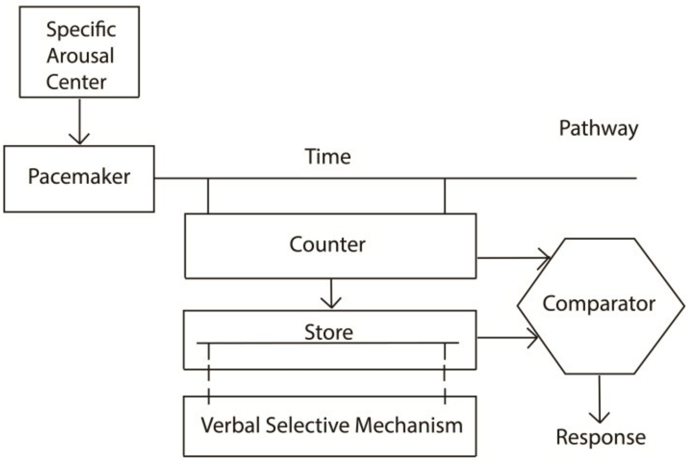

Figure 1.3. The internal clock model (adapted from Treisman, 1963). The specific arousal center influences the rate of the pacemaker. A counter counts the number of received pulses and sends this number to a store. A verbal selective mechanism acts like a long term memory storage. The comparator continuously compares the collected number of pulses (from the counter) with the retrieved number from the store. When the number of the collected pulses reaches the reference number retrieved from the store, the response takes place.

on perceived time in the range of seconds (Penton-Voak et al., 1996; Rakitin et al., 1998). The conceptual temporal unit of this internal clock model is called the pulse. The internal clock model consists of three components: 1) the pacemaker, which is the source of the pulses, 2) the counter, which simply counts the number of pulses, and 3) the comparator that compares the number of the collected pulses to the reference numbers of pulses. The reference memory is the average number of pulses from past experiences or long-term memory. Perceived duration depends on the number of collected pulses. If the comparator finds the total number of collecting pulses to be equal to the reference, it triggers a response. In contrast, if the number of the collecting pulses does not reach this reference, it requires longer time to get enough pulses and thereby a longer time to trigger a response. Alternatively, if the rate of the pacemaker is somehow accelerated and the pacemaker generates pulses more quickly than at a normal rate, the number of collected pulses would reach the reference number faster, and a response would be triggered faster.

According to the internal clock model, the rate of the pacemaker can be modulated by external stimuli, e.g., a sequence of flickers (Droit-Volet & Wearden, 2002), or clicks (Penton-Voak et al., 1996). For example, Penton-Voak et al. (1996) linked results on judged durations to differential acceleration of the pacemaker rate. To be more explicit, in one of the experiments of Penton-Voak et al. (1996), participants judged shorter durations when those durations were preceded by a sequence of clicks than when the same durations were preceded by an interval without clicks. They suggested that the preceding sequence of clicks accelerated the rate of the pacemaker, leading to shorter judged duration.

The attentional gate model

The attentional gate model (Zakay & Block, 1995) comprises a more complex internal clock (Figure 1.4). The internal clock now has 4 components; the pacemaker, the gate, the switch, and the accumulator (the latter being comparable to the counter in the internal clock model). New components in this model are the gate and the switch. The opening of the gate is modified by the internal allocation of attention (i.e., top-down processing) (Block & Zakay, 1996), while the opening of the switch is regulated by the influence of external stimuli (i.e., bottom-up processing).

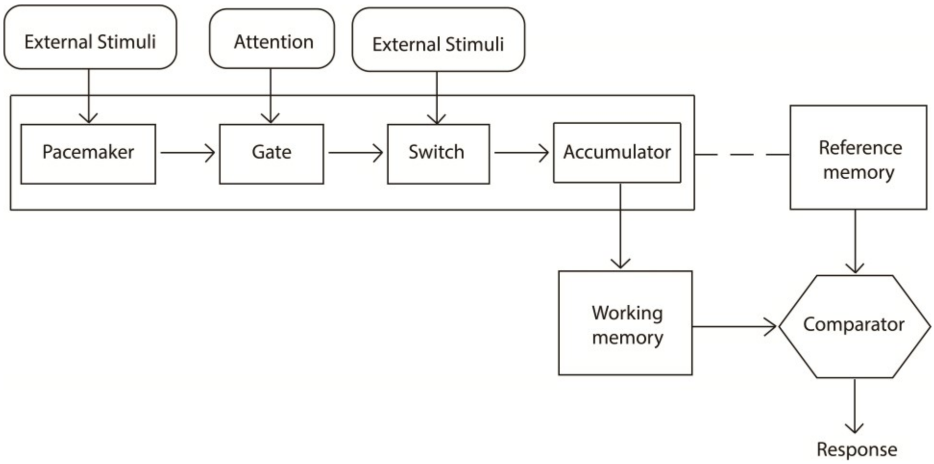

Figure 1.4. The attentional-gate model (adapted from Block and Zakay, 1996). Specific arousal from external stimuli can affect the rate of a pacemaker that releases pulses. Next, the opening of the gate depends on attentional distribution; the more attention is allocated to temporal aspects of a particular event, the wider the gate is opened. The switch is opened when a stimulus, signaling the start of an event, is detected. An accumulator counts the number of collected pulses and sends this number to working memory, and to a reference memory, to update information. Finally, the comparator compares number of collected pulses of the working memory to the reference number in the reference memory. When the number of the collected pulses reaches the reference number, the response takes place.

The attentional gate model in fact has been developed departing from a modified version of the internal clock model, i.e., the scalar timing model (Church, 1984; Gibbon, Church, & Meck, 1984) that introduced the switch, and the so-called attentional model (Thomas & Weaver, 1975) that introduced the influence of attention. Thomas & Weaver's attentional model, states that allocation of attentional resources (e.g., attention that is diverted towards non-temporal tasks) can affect temporal judgments. The attentional gate model incorporated Thomas and Weaver's attentional modulation by adding a 'gate' that is inserted between the pacemaker and the switch (Block & Zakay, 1996). In the attentional gate model, opening of the gate is controlled by attentional allocation to temporal and non-temporal information (i.e., top-down processing). The more attention is directed towards the temporal task, the wider the gate is opened or the higher number of pulses would pass and be collected.

Contextual change model

The contextual change model (Block, 1990,1992) takes into account the so-called contextual change hypothesis (Block & Reed, 1978). This hypothesis states that a higher number of changes is perceived to last longer than a lower number of changes. Various studies (Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Poynter, 1989) are in line with this contextual change model. The contextual change model (Figure 1.5) is comparable to the attentional gate model except on a few points (Block & Zakay, 1996). First, the pacemaker is substituted by the context generator, and next, the accumulator is substituted by the context recorder. The role of contextual information in the contextual change model can be compared to the role of the pulses in the previous models. Rather than just counting pulses, in the contextual change model the number of changes with respect to external stimuli is crucial. This model supports temporal judgments that involve serial or repeated events such as a sequence of spoken words (Poynter, 1983). The results of Poynter (1983)'s study supported the contextual change model and showed that segmented (i.e., discontinuous) intervals led to longer estimated durations than un-segmented (i.e., continuous)

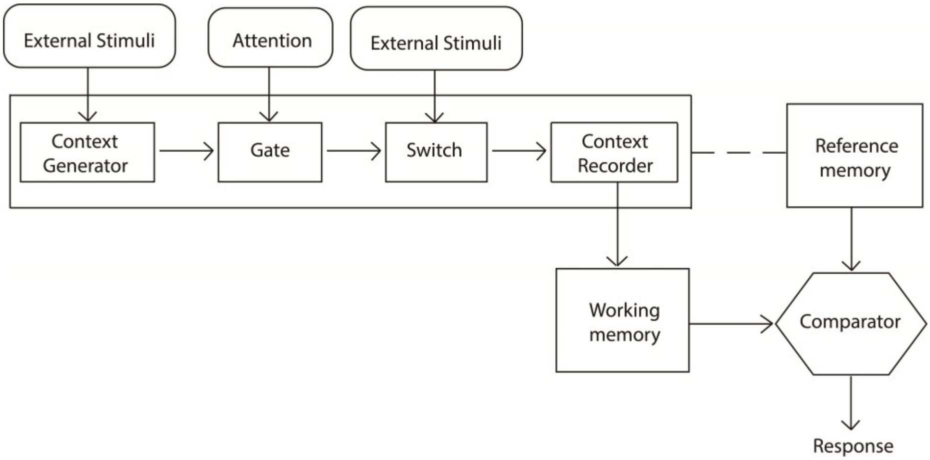

Figure 1.5. The contextual change model (adapted from Block and Zakay, 1996). This model is using a rather similar process as the attentional gate model, except that the pacemaker is now substituted by the context generator, and the accumulator is substituted by the context recorder (see text).

intervals. In addition, this contextual change model was supported by recent studies of Foley et al. (2004), and Predebon (2002). In a study of Predebon (2002), judged durations were overestimated for slow moving objects as compared to fast moving objects. They concluded that at a very fast rate of subsequent positions of displayed shape, the perceived motion appeared as a single event, but that at a slower rate, the event appeared temporally segmented into many sub-events, which was perceived to last longer than a single continuous event.

As might be clear there are many models on time perception, and the above explanations refer to just three of them. In this thesis, we refer to these models at several places. In our experiments, we measured time durations under various conditions. In the next section, we will discuss a few time estimation methods reported in the literature, some of which are employed in the next chapters. Time judgments can apply to various sensory inputs, but, as mentioned, we focus on the visual modality, thereby also investigating audiovisual cross-modal influences (i.e., from the auditory to the visual modality).

Time estimation methods

Time estimation methods can be classified into various categories (Allan, 1979; Zakay, 1993). In this thesis, we have focused on two of them. The first one is the so-called Magnitude estimation; the participant judges the temporal magnitude of a specific duration by manipulating a time scale. This is the method that we used in Chapter 2. The second time estimation method is Production; e.g., in which a button press indicates the end of a specific event (see Huber & Krist, 2004). In Chapter 3, our participants had to indicate the moment that an occluded moving object would reappear after it has disappeared behind an occluder. The duration that a moving object takes to reach a specific position is also known as time to contact (TTC) (see Baurès, Bennett, & Causer, 2015; DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003; DeLucia et al., 2016; Hecht & Savelsbergh, 2004). Besides these methods there are various other methods to estimate time duration, for example: 'Comparison' (two durations are shown and the subject responds by judging whether one is shorter, longer, or that they are equal in length), 'Reproduction' (a temporal duration is presented by the investigator and the subject responds by trying to replicate it), 'Verbal estimation' (after a presentation of a time duration, the subject states the length of that duration), and 'Ratio-setting' (the researcher shows the time duration and the subject judges an estimated duration by comparing it to the standard duration).

The Magnitude estimation paradigm that we used in Chapter 2 allows us to investigate the perceived duration of a finished event while the so-called Time To Contact (TTC) paradigm in Chapter 3 allows us to investigate perceived duration of an ongoing or expected event. Finally, in Chapter 4 we employed a spatial judgment task in which participants had to indicate the distance an object moved during a particular time interval.

Outline of the thesis

The aim of this thesis is to study spatiotemporal judgments of amodal movements. We start our investigations by examining the perceived duration of a relatively simple visual event.

Chapter 2. Here we compared the perceived duration of an object that moved across the screen to the perceived duration of a similar moving object that temporarily disappeared behind an occluder. In the first Experiment, we found differential perceived durations of occluded moving objects as compared to visible moving objects. This raised the question whether this effect was caused by occlusion per se (i.e., the non-visibility of the moving object) or by differential eye movements. More specifically, when a moving object disappears behind an occluder, participants may make an eye-saccade towards the expected point of reappearance as compared to when an object remains visible (and is perhaps tracked using smooth pursuit eye movements). Therefore, in the second experiment, we investigated whether the eye movement instructions (i.e., pursuit versus saccade instructions) or the visibility (i.e., an object moved in front or behind an occluder), influenced perceived duration.

Chapter 3. We investigate the influence of sound on amodal movements. We expected that auditory stimuli that are concurrently presented with a display showing an amodal movement may affect perceived durations of the amodal movements. Therefore, we tested such cross-modal influences of auditory patterns on temporal judgments. More specifically, the experiments deal with the influence of auditory rhythms on judged time to contact (i.e., judged moment of reappearance) of an occluded moving object. We varied rhythmic speeds of auditory sequences by varying either pause or sound durations in each experiment. We expected that a higher number of sound onsets of relatively fast rhythmic sequences would result in earlier judged reappearances than a lower number of sound onsets. We found a difference between the effects of same rhythms but different pause-sound ratios. The observed effects will then also be related to above mentioned time models.

Chapter 4. If the speed of rhythms can affect temporal judgment (i.e., TTC judgment as found in Chapter 3) of an occluded moving object, spatial judgments could be affected as well. We therefore explored the effect of an accompanying auditory rhythm on perceived distance of amodal movements. In a second experiment, we increased the number of sound onsets per unit of time for each rhythm, and we called this new factor as the ‘auditory density’. This way, we could compare the effects of auditory density and rhythm on the judged distance of occluded moving objects, revealing the strongest effect for rhythm.

Discussion and Summary. I further discuss the implications of our studies and the suggestions for future research. Finally, a summary of the thesis is provided.

2

Compressed timing of an occluded moving object: on the role of visibility and eye-movement instructions

Based on : Chotsrisuparat, C., Koning, A., Jacobs, R., & van Lier, R. (in prep.). Compressed timing of an occluded moving object: on the role of visibility and eye-movement instructions.

Abstract

Time is an important dimension of our perceived experiences. Here, we investigated whether temporary occlusion of a moving object (i.e., the tunnel effect) affects perceived duration. The tunnel effect deals with the perception of a moving object that disappears behind an occluder and then reappears at the other side of the occluder. Under proper conditions such an event is perceived as a uniform and continuous movement of a single object passing behind an occluder. We asked participants to estimate the duration of such an event and found that it was judged to last shorter than an event where an object was visible for the whole trajectory, even though in both events the objects moved with the same speed. We wanted to know whether this time compression was caused by visibility (i.e., occlusion) or whether differential eye movements might have played a role (e.g., anticipatory eye movements to the remote side of the occluder where the object was expected to reappear after occlusion). To investigate this, in a follow-up experiment participants were instructed to track an object - whether visible or occluded - in a pursuit block and alternatively, in a saccade block, make a saccade directly to the remote side of an occluder the moment the object first touched the edge of the occluder. The results support the notion that differential eye movements, but not visibility per se, lead to compression of perceived duration.

Introduction

The ability to estimate the duration of a visual event plays an important role in everyday life. A visual event may consist of both stationary objects and moving objects. The objects in these events also may not be visible all the time (like an upcoming car that temporarily disappears from sight because of other vehicles and then reappears later). The perception of continuity of an object that moves behind an occluder and then reappears was first described as the tunnel effect (Burke, 1952). The reappearing object is perceived to be the same object as the object that has gone behind an occluder, at least when spatial continuity is preserved (the object reappears at an expected location) and the time interval of the disappearance is in an optimal range (the object reappears at an expected time). Previous studies mostly focused on the perceived continuous movement and with that the persistence of a single moving object behind an occluder (Flombaum et al., 2004; Flombaum & Scholl, 2006; Flombaum et al., 2009; S. P. Johnson, Amso, & Slemmer, 2003; Kawachi & Gyoba, 2006; Michotte, Thines, & Crabbé, 1991; Rosander & von Hofsten, 2004; Scholl & Feigenson, 2004; Scholl & Pylyshyn, 1999; van der Meer, 1994). Here, we explored whether temporary occlusion of a moving object (cf. the tunnel effect) influences perceived duration as well, as compared to when a similar moving object is not occluded.

Previous studies have shown that seeing visual motion can dilate time as compared to seeing stationary objects (Au, Ono, & Watanabe, 2012; Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009). Such longer perceived duration of a moving object as compared to a stationary object can be explained by the Contextual Change model that states that more changes of visual stimuli are translated into a longer perceived duration (Block & Reed, 1978; Block & Zakay, 2006; Brown, 1995; Poynter, 1989). It is possible that occluded ('amodal') motion is just as effective as real motion in dilating perceived time. Alternatively, it is possible that perceived duration of an event with an occluded moving object (i.e., with less actual motion input) is shorter than that of an event with a visible (i.e., non-occluded) moving object. In support of the latter possibility, Terao, Watanabe, Yagi, and Nishida (2008) found that a reduction of stimulus visibility, in terms of contrast reduction, led to compression of perceived duration of a visual event. In addition, a study of Maarseveen, Paffen, Verstraten, and Hogendoorn (2017), who used a moving occluder, revealed that occlusion compressed perceived duration of a stimulus as compared to a non-occluded stimulus. Based on these visibility-related temporal modulations, it can be expected that reduced visual input in the form of temporal occlusion of a moving object (as in the tunnel effect) may also distort perceived duration.

In the following two experiments we first aimed to replicate the differentially perceived durations under occlusion conditions as compared to non-occlusion conditions. To do this, we made use of aforementioned tunnel effect. Specifically, we first investigated (Experiment 1) whether the perceived duration of an event in which a moving object is temporarily occluded differed from a similar event in which the object is continuously visible. Next (Experiment 2), we questioned whether differential eye movements might have played a crucial role. That is, from Experiment 1 it remains unknown whether potential differential results are due to visibility itself or to a differential way of looking between these conditions. For example, under occlusion participants may make a saccade to the other end of the occluder and then pick up the moving disk at the moment of reappearance. From the literature, it is known that even young babies may show such anticipatory saccadic eye-movements in similar occlusion displays (e.g., S. P. Johnson et al., 2003), and it is also known that saccadic eye movements may cause time compression (e.g., Morrone, Ross, & Burr, 2005). That is, the differential influence of pursuit tracking when the disk is visible versus saccadic eye movements when the disk is occluded could play an important role as well. In Experiment 2 we aimed to disentangle these potential factors by factorially combining them: occlusion (yes/no), eye movement instruction (pursuit/saccade).

Experiment 1

Methods

Participants

Thirty-two right-handed individuals (19 females, 13 males) ranging in age from 18 to 33 years (average age 23.41 years, SD = 3.50) participated in the experiment. All participants reported normal or corrected-to-normal vision. Each participant received course credit or a monetary reward for their time and informed consent was obtained from each participant before the experiment. This study was approved by the local ethics committee.

Stimuli

The stimulus displays, presented on a standard computer monitor, were controlled by a program that was custom written using Delphi. The target was a grey disk (1.83° diameter) that moved rightward or leftward in a linear horizontal trajectory on a white background. The total distance of the disk's trajectory was 31.82°. The occluder was a square (height = 12.10° and width = 12.10°) and was either black or white. The white occluder had exactly the same luminance properties as the background and was therefore invisible. We added this invisible (white) occluder to control for the difference in displays when comparing the non-occlusion display with the black occluder occlusion display. Note that while the white occluder is not perceived (cf. the non-occlusion display) it does trigger occlusion and continuity of the occluded disks' motions, due to the gradual deletion and accretion of the objects' contours at the borders of the occluder. Snapshots of a trial are shown in Figure 2.1.

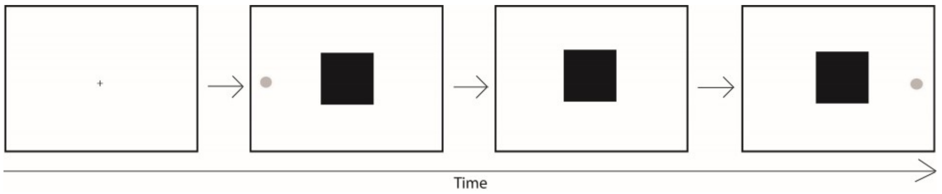

Figure 2.1. Four snapshots of visual motion in the black occluder condition. A fixation cross is presented for 1 second, and then a disk and an occluder simultaneously appear on the screen. Next, the disk starts moving across the screen along a linear horizontal trajectory. Here, after the moving disk disappears behind the occluder, the disk reappears at the remote side of the occluder and moves further towards the end of the trajectory.

Design

In order to maintain participants' attention to the task at hand from trial to trial, we created stimulus variability by having different object speeds. The duration of an event was then defined as the time it took the disk cross the screen (from start to finish). There were two blocks of event durations: Block A consisted of relatively short event durations (800 ms, 1400 ms, 2000 ms, 2600 ms, and 3200 ms) whereas Block B consisted of relatively long event durations (2800 ms, 3400 ms, 4000 ms, 4600 ms, and 5200 ms). Thus, in terms of disk speed, there were five speeds (35.63 °/s, 20.36 °/s, 14.25 °/s, 10.96 °/s, and 8.91 °/s) for the first block, and five speeds (10.18 °/s, 8.38 °/s, 7.13 °/s, 6.20 °/s, and 5.48 °/s) for the second block. The number of trials was as follows: Occluder type (3 levels; visible occluder, invisible occluder, and non-occlusion condition) × Duration (5 levels) × Blocks (2 levels; short event durations, long event durations) × 2 repetitions = 60 trials.

Procedure

Participants were seated at a distance of approximately 50 cm from a computer screen (resolution of 1280 x 1024 pixels, refresh rate 60 Hz) in a dimly lit room. They were instructed to estimate the durations of each visual event showing a disk moving across the screen. At the start of each trial, a small fixation cross was presented for 1 second after which the disk and the occluder were presented on the screen and the disk started moving. Following the disk's movement, a response screen appeared on which the participants had to judge the duration of the event by adjusting a slider on a time scale using the up and down arrows on a standard (QWERTY) keyboard followed by pressing the 'Enter' button to confirm their judgment. The time scale ranged from 0.0 s to 6.0 s with the slider set at 0.0 s as the default time. A digital display also provided the magnitude of the judged duration. There was no time limit to make a judgment and participants were asked to answer as accurately as possible. Note that we focus here on the duration of the whole event counting from when the disk began to move until it stopped moving.

Prior to the experiment, participants completed three random practice trials to become familiar with the task. Next, the experiment was administered in two blocks. The blocks were counterbalanced such that half of the participants started with block A and the other half started with block B. All 30 trials of a block were presented once in a randomized order. Participants were told in advance that the experiment comprised two blocks and that in total it would take approximately 10 minutes to complete.

Results

The participant's responses yielded the perceived duration of the visual event in each trial. Next, the ratio of the perceived duration (PD) to the actual duration (AD) of the event in a trial was calculated for each participant and each trial separately and served as the dependent variable (referred to as PD/AD ratio). In a repeated measures ANOVA, with Occluder type (3 levels; visible, invisible, non-occlusion), Duration (5 levels; shortest, short, medium, long, longest), and Block (2 levels; block A – short events, block B – long events) as the independent factors and PD/AD ratios as the dependent variable. Occluder type [$F(2,30)$ =

5.95, $p = 0.007$], Duration [$F(4,28) = 14.55$, $p < 0.001$], and Block [$F(1,31) = 41.77$, $p < 0.001$] were found significant. There was an interaction between Occluder type and Duration [$F(8,24) = 2.59$, $p = 0.034$] while no other interaction was found significant.

The main effect of Duration showed that the PD/AD ratios gradually declined from the shortest durations (1.13, SD = 0.32), short durations (1.10, SD = 0.25), medium durations (1.02, SD = 0.21), long durations (0.98, SD = 0.19) to the longest durations (0.93, SD = 0.18). The main effect of Block showed that the PD/AD ratios were higher for Block A (1.13, SD = 0.27) than for Block B (0.93, SD = 0.19). In Figure 2.2 both these main effects can clearly be seen.

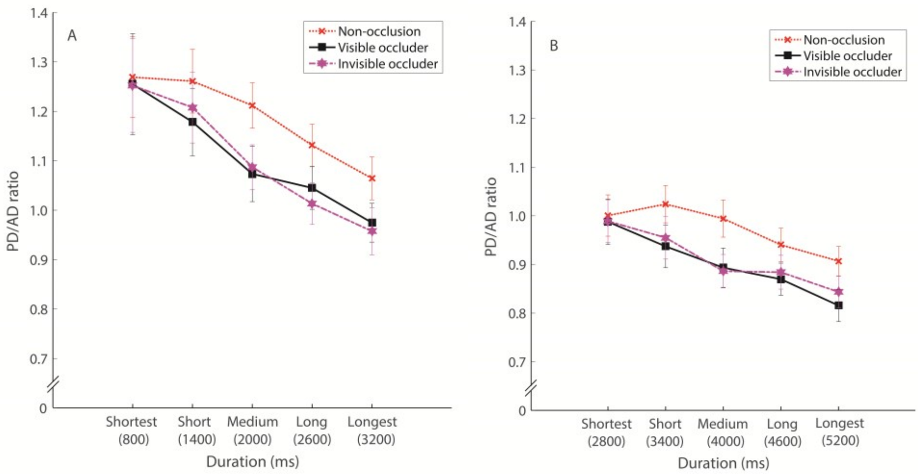

Figure 2.2. Results of Experiment 1. The average ratios of perceived duration to actual duration (PD/AD ratio) as a function of Duration, and Occluder type. The left panel presents data from Block A (relatively short event durations), and the right panel presents data from Block B (relatively long event durations). The error bars indicate +/-1 SEM.

The main effect of Occluder type shows that the PD/AD ratios of the visible occluder [$t(31) = 3.43$, $p = 0.002$] and the invisible occluder condition [$t(31) = 2.89$, $p = 0.007$] were significantly lower than the PD/AD ratios of the control (non-occlusion) condition ($p < 0.017$, Bonferroni corrected). The mean PD/AD ratios were as follows: visible occluder (1.00, SD = 0.24), invisible occluder (1.01, SD = 0.23), and non-occlusion (1.08, SD = 0.21). There was no significant difference between the PD/AD ratios of visible occluder condition and PD/AD ratios of invisible occluder condition [$t(31) = -0.64$, $p = 0.529$]. Finally, as can be seen in both panels of Figure 2.2, the interaction effect between Occluder type and Duration shows that the PD/AD ratios for the visible and invisible occluders decrease more as a function of increasing Duration (i.e., disk speed) as compared to the control (non-occlusion) condition.

Discussion

The main purpose of the first experiment was to investigate whether the perceived duration of an event showing a visible versus an occluded moving object differed from each other. First, the main effects of Duration and Block are in line with Vierordt's law (Woodrow, 1951), which states that perceived duration tends to be inversely related to the actual duration (Brown, 1995; Fortin & Rousseau, 1998). That is, short actual durations (i.e., fast moving objects) are generally judged to last longer than they actually take, while long actual durations (i.e., slow moving objects) are generally judged shorter than their actual durations. Moreover, this effect is apparently more evident when a moving object is temporarily occluded as shown by the interaction effect between Occluder type and Duration. Second, and more importantly, with regard to Occluder type, our participants judged the visual events to have a shorter duration in the occlusion conditions as compared to the non-occlusion condition. This compression of perceived duration of the occlusion conditions as compared to the non-occlusion condition is in line with the results by Maarseveen et al. (2017), but using a different set up. That is, Maarseveen et al. (2017) used a reproduction method in which participants had to replicate the duration of an event while our participants judged the perceived duration of an event on a time scale. The compressed perceived duration that we found here could indeed be based on the visibility of the moving disk (i.e., temporarily occluded versus not occluded), which would also be in line with previous studies that found perceived time to be dilated for visual motions as compared to stationary objects (Au et al., 2012; Brown, 1995). After all, similar to a condition with a stationary object, in the occluded conditions in our experiment there is no motion input during occlusion. This, in turn, is also in line with the Contextual change model. That is, events in which an object is occluded (cf., only seeing a stationary occluder) comprise fewer changes as compared to events in which an object is visible that comprise more changes, whereby the former may lead to larger time compression as compared to the latter.

Importantly, however, at this point it should be noted that the eye movements of the participants may have differed between the occlusion and non-occlusion conditions. For example, in the non-occlusion condition it is possible that participants mainly tracked the moving object from one end of the screen to the other. In contrast, in both occlusion conditions, it can be expected that as soon as the object moved behind the occluder participants were likely to make an anticipatory saccade to the other side of the occluder, and then waited for the object to reappear. Previous research showed that even from the age of three to four months, humans start to expect the reappearance of an occluded moving object and make anticipatory saccades to the location where it would reappear (S. P. Johnson et al., 2003; Rosander & von Hofsten, 2004; van der Meer, 1994). In addition to this, it is known that during and after saccades perceived durations can be compressed (Eagleman et al., 2005; Morrone et al., 2005), which could then also be an underlying cause of the results of Experiment 1. In a follow-up experiment, we therefore wanted to further test whether visibility (temporarily occluded versus not occluded) or differential eye movements were more likely to be the underlying cause of the results found in Experiment 1.

Experiment 2

We used a similar setup to Experiment 1, but now with three main variables, namely visibility, eye movement instruction, and occluder length. We now only used visible (black) occluders, since the results on the visible and invisible occluder in Experiment 1 were similar. In this second experiment, an object moved either in front of or behind an occluder. Hence, the condition in which an object moved in front of an occluder is comparable to the non-occlusion condition of Experiment 1.

Crucially, we had two eye movement instruction conditions. In the pursuit instruction condition, participants were asked to keep tracking the disk throughout a trial, also in the condition when a disk would be temporarily occluded - they then had to track the invisible moving disk as good as possible. In the saccade instruction condition, participants were asked to first track the moving disk, but then make a saccade to the remote side of the occluder as soon as the disk touched the edge of the occluder, and then track it again when it reappeared from behind the occluder all the way to the end position. Similarly to the pursuit instruction condition, these instructions applied to both visibility conditions. So, in the saccade instruction condition, when the disk would move in front of the occluder participants were instructed to make a saccade to the remote side of the occluder as soon as the disk touched the edge of the occluder and then pick up tracking again (while the disk remained visible throughout the trial). Now, if in Experiment 1 visibility was the main cause of the time modulation that was found, we expect the shortest perceived durations in the occlusion condition, irrespective of the eye movement instructions. Alternatively, if in Experiment 1 differential eye movements caused the time compression, we expect the PD/AD ratios of the saccade instruction condition to be lower than those of the pursuit instruction condition, irrespective of visibility of the disk. In other words, if differential eye movements are of decisive importance, then we expect to find a main effect for eye movement instructions, but not for visibility condition.

In addition to the two different eye movement instructions, we used two different lengths of the occluder in Experiment 2; one long occluder (i.e., longer than in Experiment 1) and one short occluder (i.e., shorter than in Experiment 1). That is, if visibility (i.e., object visible versus object invisible) influences perceived duration, then one could expect the length of the occluder to affect the perceived duration of an occluded (but not a non-occluded) moving object as well. The long occluder would then obviously lead to less visible movement of the disk as compared to the short occluder. Note that in the saccade instruction condition, the length of the occluder will also affect the instructed saccade length and not only for the occluded condition, but also for the non-occluded condition. Hence, adding occluder length as an additional factor can possibly help to elucidate the relative contribution of both visibility and eye movement instructions.

Methods

Participants

Twenty-seven right-handed individuals (19 females, 8 males) ranging in age from 18 to 33 years (average age 20.59 years, SD = 2.78) participated in this experiment. All participants reported normal or corrected-to-normal vision. Each participant received course credit or a monetary reward for their time and informed consent was obtained from each participant. This study was approved by the local ethics committee.

Stimuli

The visual events were similar to those of Experiment 1 wherein a grey disk moved from one side of the screen to the other. In contrast to the first experiment, now no invisible occluder was used, while eye movement instructions and occluder length were added as factors. In addition, we chose only three levels of duration, more specifically, from block B in Experiment 1 (i.e., durations 2800 ms, 4000 ms, and 5200 ms). The occluder lengths were 6.07°, and 18.07° (the height was 6.07° for both occluders). An example of a trial is shown in Figure 2.3.

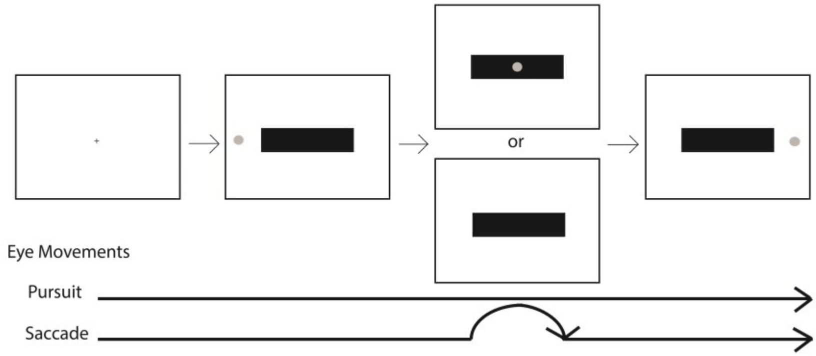

Figure 2.3. The schematic representations show a few displays during the moving sequence of a trial (long occluder condition), and eye movement instructions (pursuit vs saccade).

Design

There were two eye-movement instruction blocks, pursuit instruction versus saccade instruction. The number of trials in each eye movement instruction block was as follows: Visibility (2 levels; object moves in front of the occluder, object moves behind the occluder) × Duration (3 levels; 2800 ms, 4000 ms, and 5200 ms) × Occluder length (2 levels; short and long) × 10 repetitions = 120 trials. So, given the two eye-movement instruction blocks, the total number of trials per participant was 240 trials.

Procedure

Participants were seated at a distance of 50 cm in front of a computer screen (resolution of 1280 x 1024 pixels, refresh rate 120 Hz) in a dimly lit room. They were also instructed to avoid blinking when the stimuli were presented on the screen and to avoid head movements during the experimental session. (An eye-tracker was used, which by itself helped the participant to adhere to the instructions; although we could not use the recordings, presumably due to code errors, conclusions regarding the influence of the differential instructions can still be drawn.)

Similar to Experiment 1, the task was to judge the duration from the moment the disk started to move until it stopped at the other side of the screen. Judgments were made on a time scale using a mouse to manipulate a slider, followed by clicking an 'OK' button under the time scale to confirm the judgments. Note that, the time scale was designed to show the scale at regular intervals between 0.0 s to 8.0 s. We chose to increase the time scale range compared to Experiment 1 to ensure that the margins between the extrema of the time scale and the range of durations used in both experiments were the same.

For each participant, all 120 trials were randomized and the same randomized set of 120 trials was used for both eye movement instruction blocks. There were two eye movement instruction blocks; pursuit and saccade. The order of eye movement instruction blocks was counterbalanced across participants. Prior to each block, four random practice trials were presented to become familiar with the instructions. There was a 5-minute break between the two eye movement instruction blocks. The experiment took approximately 60 minutes to complete.

Results

Similar to the results of Experiment 1, the ratio of perceived duration (PD) of a visual event to the actual duration (AD) of a visual event, the PD/AD ratio, was calculated for each participant and each trial separately. A repeated measures ANOVA was run with Eye movement instruction (2 levels; pursuit instruction, saccade instruction), Occluder length (2 levels; short, long), Visibility (2 levels; occluded, non-occluded), and Duration (3 levels; 2800 ms, 4000 ms, 5200 ms) as independent factors, and PD/AD ratio as the dependent variable. Main effects were found for Eye movement instruction [$F(1,26) = 4.84$, $p = 0.037$], Occluder length [$F(1,26) = 8.85$, $p = 0.006$], and Duration [$F(2,25) = 13.35$, $p < 0.001$]. In addition, there was an interaction between Eye movement instruction and Visibility [$F(1,26) = 4.94$, $p = 0.035$]. No other effects were found.

The main effect of Eye movement instruction revealed that the PD/AD ratio (0.90, SD = 0.20) of the saccade condition was significantly lower than the PD/AD ratio of the pursuit condition (0.94, SD = 0.16). For the main effect of Occluder length it turned out that the PD/AD ratio of the long occluder (0.94, SD = 0.16) was larger than that of the short occluder (0.89, SD = 0.19). Finally, similar to Experiment 1, the main effect of Duration showed that the PD/AD ratios decreased with increasing durations, with 0.95 (SD = 0.20), 0.92 (SD = 0.17), 0.88 (SD = 0.16), for the durations 2800 ms, 4000 ms, and 5200 ms respectively. The interaction between Eye movement instruction and Visibility is shown in Figure 2.4. The average PD/AD ratios of the pursuit-instruction/occluded condition was 0.94 (SD = 0.17) and of the pursuit-instruction/non-occluded condition was 0.95 (SD = 0.16). In addition, the PD/AD ratios of the saccade-instruction/occluded condition was 0.89 (SD = 0.19) and of the saccade-instruction/non-occluded condition was 0.89 (SD = 0.20). To further investigate the interaction effect, we applied posthoc t-tests; it turned out that, after Bonferroni correction, none of the pairwise comparisons reached significance.

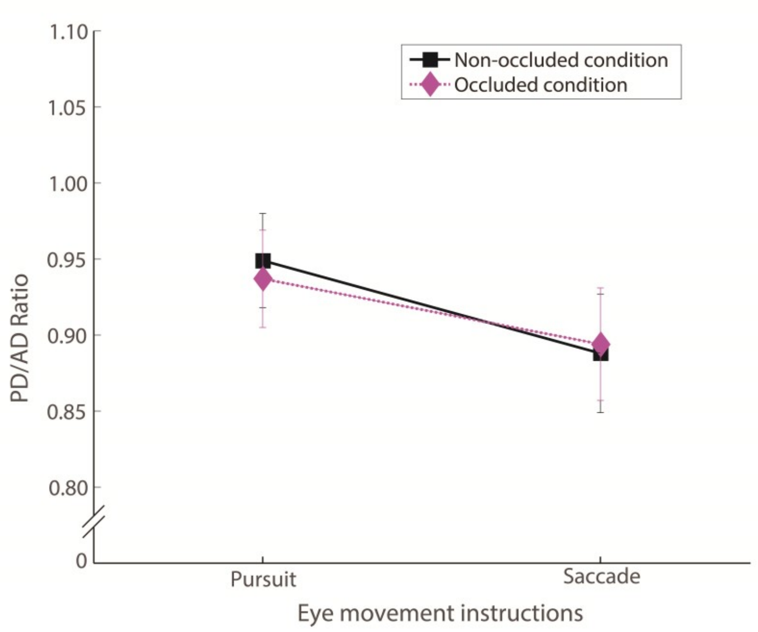

Figure 2.4. Results of Experiment 2. The average ratios of perceived duration to actual duration (PD/AD ratio) as a function of Eye movement instruction and Visibility. The error bars indicate +/-1 SEM.

Discussion

In this second experiment, we investigated whether visibility of the disk (i.e., occluded versus non-occluded) or eye movement instructions (pursuit versus saccade) may have triggered the compression of the perceived durations of occluded moving objects that was found in Experiment 1. With regard to the main effects, first of all, we found a main effect of Duration. This effect was similar to Experiment 1, in line with Vierordt's law (Woodrow, 1951) and as no other interactions with this factor was found, it will therefore not be discussed further. Second, the main effect of Occluder length showed that more time compression was found for the short occluder as compared to the long occluder. Third, in the saccade instruction condition time compression was found to be larger than in the pursuit instruction condition. In contrast to Experiment 1, we found no main effect of Visibility (i.e., occluded condition vs non-occluded condition). However, Visibility did interact with Eye movement instruction. In sum, these effects together seem to indicate already that not visibility, but rather eye movements are more likely to trigger time compression.

The main effect of Occluder length, with more time compression found for the short occluder than the long occluder, is rather unexpected. That is, we reasoned that if Visibility would influence perceived duration, a modulation of perceived duration due to variation in Occluder length could then also be expected. However, neither a main effect of Visibility, nor an interaction between these two variables was found. Instead, more time compression was found for the short occluder as compared to the long occluder. Note that this main effect also does not readily fit with the Contextual change model wherein more changes are expected to lead to longer perceived durations. As the main effect of Occluder length was also not modulated by Eye movement instruction, other factors like the role of divided attention might have played a role as well. We will return to that in the General Discussion.

The main effect of Eye movement instruction revealed that in the saccade instruction condition perceived duration was shorter than in the pursuit instruction condition. This supports the notion that differential eye movements, but not visibility per se, caused the difference in perceived duration. Note, however, that the interaction effect between Eye movement instruction and Visibility revealed that visibility still had a subtle effect on perceived duration. Although not significant as evidenced by the post-hoc tests, the data do suggest that the pursuit instruction condition resulted in more compression when the object was occluded as compared to when it was not occluded, perhaps because more saccades are made.

General discussion

The aim of this study was to investigate the influence of temporary occlusion of a moving object on perceived duration as compared to a non-occluded moving object. We tested this by having participants judge durations of visual events, a (non-)occluded object moving with various speeds (but always travelling the same distance) from one side of the screen to the other, on a time scale. The results from Experiment 1 showed that participants judged the durations of visual events to be shorter when a disk was temporarily occluded than when the disk remained visible. In order to find the cause of this time compression of the occluded moving objects, we ran a second experiment in which we manipulated the visibility of the objects while at the same time instructed participants to make differential eye movements.

In Experiment 2, participants were instructed to either track a moving disk (pursuit instruction condition), also when it was temporarily occluded, or to perform a saccade to the other side of the occluder the moment the moving object first touched the edge of the occluder (saccade instruction condition). We found that the saccade instruction condition led to larger time compression than the pursuit instruction condition. Visibility of the disks did not result in a difference in perceived duration. This result on eye movement instructions is in line with previous studies that showed that saccades are involved with a compressed duration of temporal judgments (Kusunoki & Goldberg, 2003; Morrone et al., 2005; Nakamura & Colby, 2002). That is, typically, time estimation was found to be compressed during and after saccades (Eagleman et al., 2005; Morrone et al., 2005). These findings can perhaps be explained by the fact that the lateral intraparietal area is both sensitive to saccade performance (Kusunoki & Goldberg, 2003; Nakamura & Colby, 2002) and to duration encoding (Leon & Shadlen, 2003).

In the both instruction conditions, there might have been great variability in following the specific eye movement instructions. Future studies should further zoom in on this. Specifically, it is known that pursuit tracking is extremely difficult especially when objects are not visible. Alternatively, making an anticipatory saccade while an object remains visible may trigger covert attentional processing, and with that possible reflexive eye movements to the approaching object. Accurate eye movement data could have shed more light on how well participants were able to follow the instructions. However, it seems reasonable to assume that, overall, the actual eye movements comprised a mix of pursuit tracking and saccades but that in saccade instruction condition more saccades were being made than in the pursuit tracking condition, and that more pursuit tracking was being performed in the pursuit instruction condition than in the saccade instruction condition. Crucially here is that the differential instructions (saccade versus pursuit) led to a significant main effect while there was no effect of Visibility. This supports the notion that in Experiment 1, a difference between eye movements played a decisive role regarding the time compression, not occlusion per se.

In addition to these findings, the relation between eye movements and time compression in the current paradigm does need further investigation. A factor that has been briefly touched upon above that might have played a role concerns attention. According to the Attentional allocation, or time-sharing model, a higher attentional demand of a concurrent task can lead to shorter perceived time on a temporal judgment task (Brown, 1997; Fortin, 2003; Macar, Grondin, & Casini, 1994; Sawyer, Meyers, & Huser, 1994). We instructed participants not to blink during the trial for both saccade and pursuit instruction condition. In addition, in the pursuit instruction condition participants had to track the disk for both the short and long occluders while in the saccade instruction condition they were asked to execute a saccade, which could be short or long, depending on the occluder length. It could be that, due to the relative difficulty of these eye movement tasks, differential divided attention influenced the results; for example, when more attention was paid to control the eye movements, less attention was perhaps focused on the actual task (i.e., judging the duration), which may then also have led to more time compression. As a consequence of these specific instructions and also linked to the concept of attention, it could be that waiting time played a role as well. For example, when a saccade to the other side of the occluder was made, the participant was instructed to wait until the disk appeared and then pick up tracking again towards the end of the disk's movement. It might very well be that such a waiting period also influences time compression. A previous study of Fortin and Massé (2000) revealed that a break (i.e., interval of stimulus disappearance) followed by a long waiting time can lengthen judged duration. Thus, in our experiment, after a saccade was instructed to be made, the resulting waiting time may have lengthened the perceived duration. Since this waiting time is then obviously longer in case of the long occluder than in case of the short occluder in Experiment 2, it can be expected that this counteracted initial time compression effects due to any saccade that was just being made.

Finally, another issue that possibly needs further study is the time judgment procedure itself. For example, the temporal judgment used here (i.e., judging the duration magnitude of a visual event by manipulating a time scale) at the end of an event is in part based on memory, in any case more than real-time motion extrapolation (which would be the case if one for example had to judge the moment of reappearance of a disappeared object). In our recent study (Chotsrisuparat, Koning, Jacobs, & van Lier, 2017), we tested such temporal judgments using a task in which participants actually had to respond the moment an object would reappear after passing behind an occluder.

In conclusion, the current results show that while occlusion at first face seem to lead to time compression, this appears not to be the case. The current results rather suggest that differential eye movements more likely underly time compression found in this study. Future research could further disentangle various factors, especially the role of attention.

3

Auditory rhythms influence judged time to contact of an occluded moving object

Based on : Chotsrisuparat, C., Koning, A., Jacobs, R., & van Lier, R. (2017). Auditory rhythms influence judged time to contact of an occluded moving object. Multisensory Research, 30(7-8), 717-738.

Abstract

We studied the expected moment of reappearance of a moving object after it disappeared from sight. In particular, we investigated whether auditory rhythms influence time to contact (TTC) judgments. Using displays in which a moving disk disappears behind an occluder, we examined whether an accompanying auditory rhythm influences the expected TTC of an occluded moving object. We manipulated a baseline auditory rhythm — consisting of equal sound and pause durations — in two ways: either the pause durations or the sound durations were increased to create slower rhythms. Participants had to press a button at the moment they expected the disk to reappear. Variations in pause duration (Experiments 1 and 2) affected expected TTC, in contrast to variations in sound duration (Experiment 3). These results show that auditory rhythms affect expected reappearance of an occluded moving object. Second, these results suggest that temporal auditory grouping is an important factor in TTC.

Introduction

In everyday life, we see many moving objects around us and we can envision the forthcoming movements of those objects. We can even estimate the moment of reappearance of a moving object when it temporarily moves behind an occluder (cf. Burke, 1952). The estimated duration that a moving object takes to reach a specified location is called time to contact (TTC) (e.g., Baurès et al., 2015; DeLucia et al., 2003; Hecht & Savelsbergh, 2004). The time it takes for an occluded (but previously visible) object to reach a specific location, e.g., the other side of the occluder, is an example of TTC. Previous studies found that people use multiple cues (e.g., moving speed) in estimating TTC (DeLucia et al., 2003; Hecht & Savelsbergh, 2004). Certain manipulations lead to systematic distortions in these estimates (Baurès et al., 2015; Huber & Krist, 2004). For example, Huber and Krist (2004) found that observers underestimated the time of reappearance of a dropping ball, an effect possibly mediated by prior knowledge (i.e., of gravitational pull). Also, moving distractor objects affect the ocular pursuit of an occluded moving object, in this case leading to an overestimation of the TTC (Baurès et al., 2015). We expected that not only prior knowledge or moving stimuli from the same visual modality can influence TTC, but that stimuli from other sensory modalities can do so as well (e.g., auditory stimuli).

It is known that auditory stimuli affect temporal estimations (Horr & Di Luca, 2015; Wearden et al., 2007). As we expect timing to be a supramodal process (e.g., Hanson, Heron, & Whitaker, 2008), we expect auditory stimuli to affect the timing of visual movements as well. With respect to expectations of visual movements, trajectories of visual objects are completed (or filled in) when parts of these trajectories are occluded (the Tunnel Effect, cf. Burke, 1952; Flombaum & Scholl, 2006; Flombaum, Scholl, & Pylyshyn, 2008; Kawachi & Gyoba, 2006; Michotte et al., 1991). Since there is no direct perception of the occluded object, but its presence is inferred or felt, the object is said to be perceived 'amodally'. We will therefore refer to occluded movement as 'amodal movement' and we expect that auditory stimuli can affect the perception of these amodal movements.

There are many cross-modal studies that show effects of the temporal structure of auditory stimuli on the interpretation of a visual event (Roseboom, Kawabe, & Nishida, 2013; Sekuler, Sekuler, & Lau, 1997; Shams et al., 2002; Watanabe & Shimojo, 2001). For example, some studies show that a brief sound at the moment that two objects cross paths can bias perception of the two objects as bouncing against each other rather than moving across each other (Sekuler et al., 1997; Watanabe & Shimojo, 2001). Moreover, this perception of bouncing decreases when two similar sounds are presented at 300 ms before and after the concurrent sound at the bouncing point (Watanabe & Shimojo, 2001). Watanabe and Shimojo suggest that auditory grouping might play a role in dealing with the ambiguity of this visual scene. In another example of cross-modal effects of temporal structure of auditory stimuli, where a single visual flash is accompanied by two consecutive sounds, two flashes tend to be perceived instead of just one (Shams et al., 2002). Moreover, people do not see this illusion when the two sounds are of a different pitch, again suggesting that auditory grouping, here based on similarity in sound, is important (Roseboom et al., 2013).

Hence, grouping of similar sounds seems to influence temporal judgments of visual events. In line with the auditory grouping effect on visual judgments, previous studies have also shown that audition appears to dominate vision in the temporal domain, especially when concerning rhythmic patterns (Repp & Penel, 2002, 2004). For example, people are better able to tap in line with rhythmic auditory stimuli than with rhythmic visual stimuli (Patel, Iversen, Chen, & Repp, 2005). Rhythmic auditory stimuli can also guide temporal attention in the visual field, and influence the speed of responding to a visual event (K. A. Johnson, Bryan, Polonowita, Decroupet, & Coull, 2016; Sanabria, Capizzi, & Correa, 2011). Therefore, we propose that the temporal structure of rhythmic auditory stimuli might affect the TTC response of an expected visual event as well.

Previous audiovisual studies (Hofbauer et al., 2004; Wuerger et al., 2010) investigated TTC judgments of successively presented clicks and flashes (i.e., both temporally and spatially separated) before occlusion, and found that bimodal presentations reduced variability of TTC judgments as compared to the unimodal presentation of either visual or auditory stimuli. Both above mentioned TTC studies used moving auditory stimuli, in which the sound source also moved (e.g., came from differently located loudspeakers), and focused on the influence of bimodal versus unimodal stimuli on TTC judgments. In the present study, however, we are concerned with the effect of the temporal structure of the auditory rhythms during occlusion and its possible influence on TTC judgments of amodal movements. We therefore chose to present auditory stimuli from non-moving sources, in order to focus entirely on the temporal structure of the auditory rhythms.

We used a single object that moved in a horizontal direction to prevent the influence of gravitational knowledge, and participants could move their eyes freely. We expected that the updating of the position of the occluded object and the predicted TTC are influenced by input from concurrent auditory rhythms (i.e., sound/pause alternations). In our experiments, participants had to judge when an occluded moving object would reappear at the other side of the occluder, while moving at a constant speed before occlusion, and while accompanied by an auditory sequence from the moment of occlusion. With regard to the auditory sequences, we define ‘rhythm’ in our study as the alternation between sounds and pauses. We created a baseline auditory rhythm that comprised a relatively fast alternation of equal sound and pause duration (each 100 ms). Next, we created two types of auditory sequences with slower rhythms. That is, we increased either the pause durations (Experiments 1, 2, and 4), or the sound durations (Experiments 3 and 4). We expected that the judged TTC of an expected visual event would be influenced by the temporal structure (e.g., pause duration or sound duration, or number of sound onsets) of the auditory rhythms.

Concerning the expectations, it has been shown that the characteristics of sounds can modulate perceived visual motion, location, or even direction (Hidaka, Teramoto, & Sugita, 2015; Hubbard & Courtney, 2010). Also, prior experiences or knowledge can build up an association between audition and vision. For example, a high pitch tends to be associated with an inclining slope while a low pitch tends to be associated with a declining slope (Parrott et al., 2015); or the remembered location of a horizontally moving object was judged to be more downward when accompanied by sounds that descended in frequency than by sounds that ascended in frequency (Hubbard & Courtney, 2010). Similarly, we assume that relatively fast rhythms are more easily associated with fast (visual) movements, and relatively slow rhythms with slow (visual) movements. Based on this assumption we anticipate that objects moving behind an occluder will be expected to reappear faster at the other side of the occluder when they are accompanied by a fast rhythm than when accompanied by a slow rhythm. Therefore, we hypothesize that relatively fast rhythms lead to shorter TTC judgments, while relatively slow rhythms lead to longer TTC judgments.

Experiment 1

In this first experiment we examined whether variations in a rhythm accompanying an occluded moving disk would affect the expected moment of reappearance at the other side of the occluder.

Methods

Participants

Twenty-seven participants (21 females) ranging in age from 19 to 42 years (average age 21.44 years, SD = 4.67) participated in the experiment. All participants reported normal hearing, and normal or corrected-to-normal vision. One participant was a volunteer without receiving course credits and the others received course credits in return for their participation. Informed consent was obtained from each participant before the experiment. This study was approved by the local ethics committee.

Stimuli

The visual stimuli were displayed on a computer screen, and the visual and auditory displays were controlled by a program that was custom written using Delphi. Each display comprised a grey disk (2.0° diameter), that served as a moving object and a black rectangle (height = 3.9° and width = 18.7°) that served as an occluder. Both were presented on a white background. During a trial, the grey disk always followed a linear horizontal trajectory (from left to right or vice versa). The disk never actually reappeared at the other side of the occluder, i.e., no feedback on performance was given. Snapshots of a single trial are shown in Figure 3.1. The total angular distance that the grey disk moved was 5.7°.

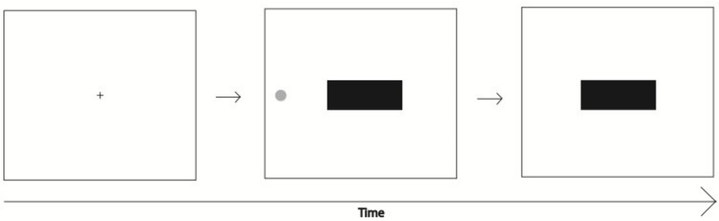

Figure 3.1. Schematic representation of Experiment 1 showing three displays of a visual stimulus sequence.

We used CoolEdit Pro 2.1 (Adobe Systems, Inc.) to generate a sinusoidal soundwave with a frequency of 1500 Hz, lasting for 100 ms. Next, using this soundwave, two rhythmic sequences were generated, i.e., a fast and a slow alternation of sounds. More specifically, to create the different rhythm conditions, 100 ms sounds were alternated with 100 ms pauses (i.e., to create the condition shown in Figure 3.2B) or with 300 ms pauses (i.e., to create the condition shown in Figure 3.2C).

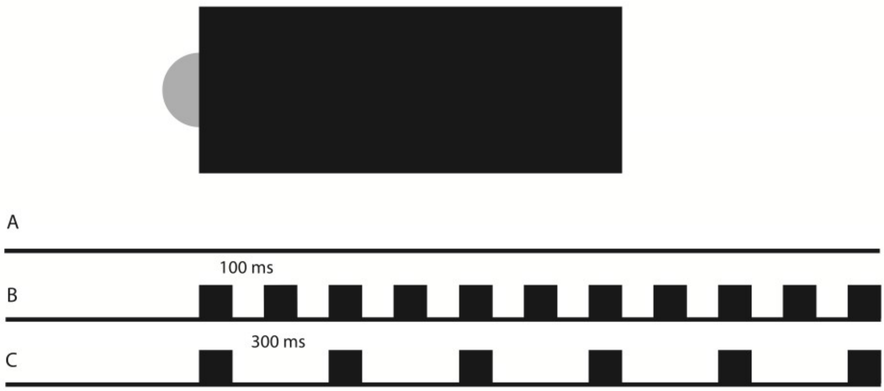

Figure 3.2. Schematic diagram of Experiment 1 showing the auditory and visual stimuli. The auditory sequence starts to play when the center of the object reaches the leading contour of the occluder. Each solid rectangle represents a 100 ms sound: (A) No-sound condition; (B) Fast rhythm, i.e., 100 ms sounds alternated with 100 ms pauses; (C) Slow rhythm, i.e., 100 ms sounds alternated with 300 ms pauses.

Design

In order to increase the uncertainty in the time of the object's reappearance, different speeds (in visual angle per second) of the grey disk were used. In total, there were 60 unique trials: Rhythm (three levels; No-sound, Fast rhythm, and Slow rhythm) × Disk speed (10 levels; 5.0°/s, 5.5°/s, 6.0°/s, 6.7°/s, 7.5°/s, 8.6°/s, 10.0°/s, 12.0°/s, 15.1°/s, and 20.1°/s) × Movement direction (two levels; leftward and rightward).

Procedure

Participants were seated at a distance of approximately 70 cm in front of the computer screen (resolution 1280 × 1024 pixels, refresh rate 60 Hz). Two loudspeakers were placed on both sides of the screen and the loudness was calibrated at 68 decibels. Each trial started with a fixation cross that was presented for 2 s, followed by the presentation of the grey disk and the black rectangle. By clicking a button on a button box with their dominant hand, participants made the grey disk move at a constant speed, until it disappeared behind the occluder. When the disk disappeared, no sound was played (condition A as shown in Figure 3.2) or a Fast rhythm or Slow rhythm started to play (as shown in Figure 3.2 conditions B and C).

Note that the sound started to play the moment the center of the disk reached the first side of the occluder and only stopped playing when a response was given. Participants were instructed to judge at what moment the grey disk would reappear by clicking the same button and to respond as accurately as possible. After that, the next trial started. The time limit of each trial was 12 seconds. All 60 trials were presented once in a random order in a single block, and three blocks were administered. Each participant thus received a total of 180 trials. Before starting the first block, participants completed two random practice trials to get familiar with the trials. The entire experiment took approximately 20 minutes per participant.

Results

The ratio of the judged time to contact (JTTC) and the actual time to contact (ATTC) was calculated for each participant and each condition separately, which then served as the dependent variable (referred to as JTTC/ATTC ratio). The JTTC/ATTC ratios of the No-sound, 100 ms pause duration, and 300 ms pause duration conditions were: 1.15 (SD = 0.27), 1.16 (SD = 0.26), and 1.21 (SD = 0.25), respectively (Figure 3.3). One-sample t-tests showed that the average JTTC/ATTC ratios for all conditions were significantly higher than 1.00: No-sound [$t(26) = 2.97$, $p = 0.006$], 100 ms pause [$t(26) = 3.36$, $p = 0.002$], and 300 ms pause [$t(26) = 4.46$, $p < 0.001$].

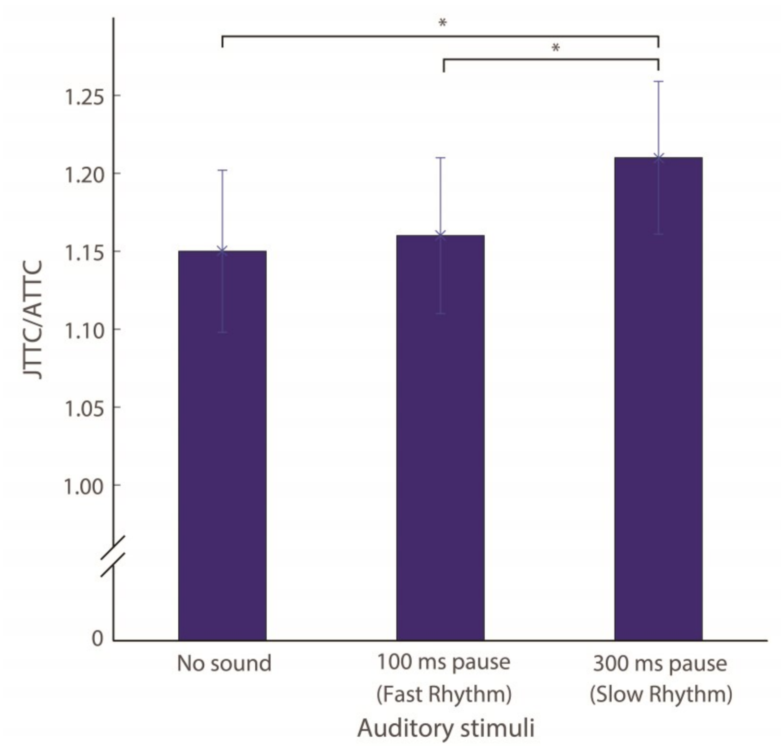

Figure 3.3. Results of Experiment 1. Average ratios between judged time to contact and actual time to contact (JTTC/ATTC ratios). Error bars indicate +/-1 SEM.

A repeated-measures ANOVA, with Rhythm (three levels), Disk speed (10 levels), and Movement direction (two levels) as the independent factors and JTTC/ATTC ratio as the dependent variable yielded significant main effects for Rhythm [$F(2,25) = 15.76$, $p < 0.001$], and Disk speed [$F(9,18) = 9.97$, $p < 0.001$]. No other main effects or interactions were significant. For Rhythm, it was found that the average JTTC/ATTC ratio in the Slow rhythm condition was longer than the No-sound and the Fast rhythm conditions (see also Figure 3.3). That is, pairwise t-test ($p < 0.017$, Bonferroni-corrected) comparisons showed that the JTTC/ATTC ratios of the Slow rhythm condition were significantly higher than the JTTC/ATTC ratios of the Fast rhythm condition [$t(26) = -5.44$, $p < 0.001$], and the No-sound condition [$t(26) = -5.11$, $p < 0.001$]. There was no significant difference between the Fast rhythm condition and the No-sound condition [$t(26) = -0.90$, $p = 0.374$].

For the factor Disk speed, Within-Subjects Contrasts Analyses revealed that the quadratic component was significant [$F(1,26) = 22.83$, $p < 0.001$]. The JTTC/ATTC ratios displayed an inverted U-shaped curve as a function of speeds (see the supplemental information, Figure S3.1). In other words, the overestimation of the TTC was strongest for the middle disk speeds.

Discussion

This first experiment aimed to test whether variation in an auditory rhythm would influence the judged moment of reappearance of an occluded moving object. Let us first make some general observations. First, in all conditions, with or without accompanying rhythms, objects appeared to move slower than they actually were. We speculate that this phenomenon could be based on known laws of physics, particularly laws dictating that friction should lead to slowing down of objects (Hubbard, 1995). This explanation would explain why objects appear to move slower in the horizontal direction, while previous results indicate that they appear to move faster when falling down, possibly as a result of knowledge about gravitational pull (Huber & Krist, 2004).

Second, as shown by the main effect of Disk speed, we found that the participants tended to judge TTC more accurately for the fastest and slowest disk speeds, and tended to overestimate the TTC for intermediate disk speeds. Possibly, participants were uncertain about the intermediate disk speeds. However, Disk speed is not the target factor that we wanted to investigate so we will not discuss further.

Now that we made these general observations, we move on to our main finding, that the auditory rhythms did exert an influence on the judged speed of the occluded disk. The object was judged to be moving even slower, compared to the other conditions, when it was accompanied by the slow auditory rhythm, as predicted by our hypothesis. It thus appears that between our fast rhythm (100 ms pause duration) and our slow rhythm (300 ms pause duration), there is a critical pause duration that leads participants to further increase their estimations of TTC. In the following experiment we have extended the range of pause durations used, to include a 200 ms pause, and also a 400 ms pause.

Experiment 2

In order to more closely investigate whether a critical pause duration can be found, we repeated the experimental procedure of Experiment 1, but now adding two more pause duration conditions (i.e., 200 ms and 400 ms). Thus, in Experiment 2, the moving object was accompanied by one of four different rhythms or no sound accompanied the object.

Methods

Participants

Twenty-three participants (20 females) ranging in age from 18 to 23 years (average age 20.52 years, SD = 1.53) participated in the experiment. One participant also took part in the first experiment. All participants reported normal hearing, and normal or corrected-to-normal vision. In return, all participants received course credit, and informed consent was obtained from each participant before the experiment started. This study was approved by the local ethics committee.

Stimuli

The visual stimuli were the same as in Experiment 1, but a broader range of auditory stimuli was employed. More specifically, the 100 ms sounds were alternated with 100, 200, 300, or 400 ms pauses. The various speeds of the grey disk were identical to Experiment 1. In Figure 3.4, a schematic diagram shows the five different rhythm conditions.

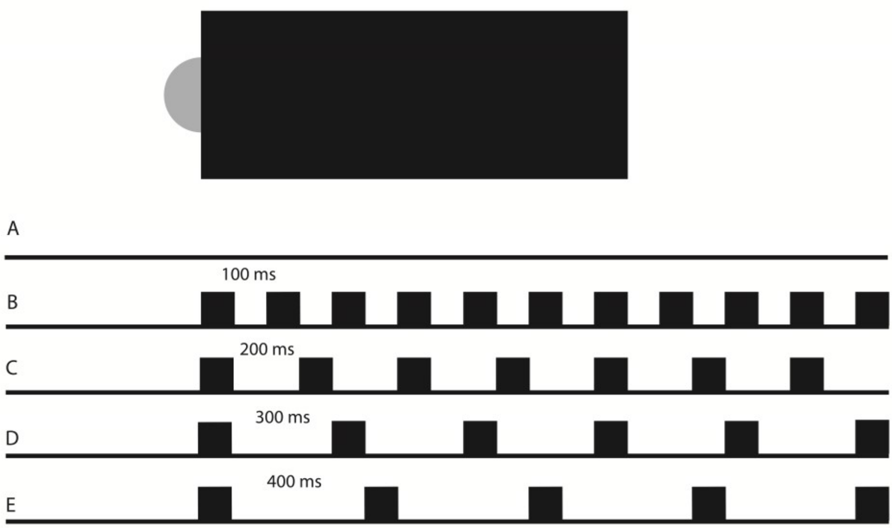

Figure 3.4. Schematic diagram of Experiment 2 showing the auditory and visual stimuli. The auditory sequence starts to play when the center of the object reaches the leading contour of the occluder. Each solid rectangle represents sound: (A) No-sound condition; (B) 100 ms sounds alternated with 100 ms pauses; (C) 100 ms sounds alternated with 200 ms pauses; (D) 100 ms sounds alternated with 300 ms pauses; (E) 100 ms sounds alternated with 400 ms pauses.

Design

In total, there were 100 unique trials: Rhythm (five levels; No-sound, 100 ms pause duration, 200 ms pause duration, 300 ms pause duration, and 400 ms pause duration) × Disk speed (10 levels; 5.0°/s, 5.5°/s, 6.0°/s, 6.7°/s, 7.5°/s, 8.6°/s, 10.0°/s, 12.0°/s, 15.1°/s, and 20.1°/s) × Movement direction (two levels; leftward and rightward).

Procedure

The procedure was the same as that of Experiment 1 except that each of the three blocks was now composed of 100 unique trials. Therefore, each participant received a total of 300 trials. Before starting the first block, participants completed three random practice trials to get familiar with the trials. The whole experiment took approximately 40 minutes to complete.

Results

The ratios between average judged time to contact and actual time to contact (JTTC/ATTC) of the five Rhythm conditions were calculated for each condition and each participant separately. The means of these ratios were: No-sound (1.22, SD = 0.17), 100 ms pause (1.22, SD = 0.18), 200 ms pause (1.24, SD = 0.19), 300 ms pause (1.28, SD = 0.20), and 400 ms pause (1.29, SD = 0.22) (Figure 3.5). One-sample t-tests showed that the average JTTC/ATTC ratios of all conditions were significantly higher than 1.00: No-sound [$t(22) = 6.04$, $p < 0.001$], 100 ms pause [$t(22) = 6.08$, $p < 0.001$], 200 ms pause [$t(22) = 5.93$, $p < 0.001$], 300 ms pause [$t(22) = 6.75$, $p < 0.001$], and 400 ms pause [$t(22) = 6.32$, $p < 0.001$].

A repeated-measures ANOVA was run with Rhythm (five levels), Disk speed (10 levels) and Movement direction (two levels) as the independent factors and JTTC/ATTC ratio as the dependent variable. The factors Rhythm [$F(4,19) = 7.39$, $p = 0.002$] and Disk speed [$F(9,14) = 8.15$, $p < 0.001$] yielded significant main effects. Movement direction was also significant [$F(1,22) = 6.24$, $p = 0.032$]. The average JTTC/ATTC ratio of the objects that moved in the rightward direction (1.24, SD = 0.18) was lower than in the leftward direction (1.26, SD = 0.20). None of the interactions reached significance.

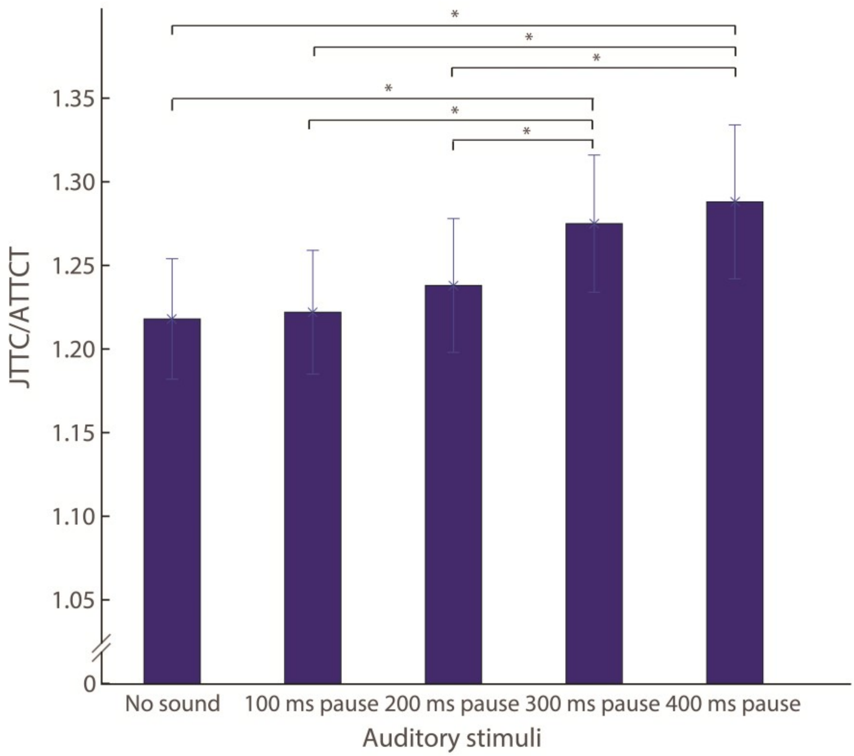

Figure 3.5. Results of Experiment 2. Average ratios between judged time to contact and actual time to contact (JTTC/ATTC ratios). Error bars indicate +/-1 SEM.

Pairwise *t*-test ($p < 0.005$, Bonferroni-corrected) comparisons showed that the JTTC/ATTC ratios of the 400 ms pause condition were significantly higher than the JTTC/ATTC ratios of the No-sound condition [$t(22) = -4.10$, $p < 0.001$], the 100 ms pause condition [$t(22) = -3.95$, $p = 0.001$], and the 200 ms pause condition [$t(22) = -5.18$, $p < 0.001$] (see also Figure 3.5). In addition, the JTTC/ATTC ratios of the 300 ms pause condition were significantly higher than the JTTC/ATTC ratios of the No-sound condition [$t(22) = -3.56$, $p = 0.002$], the

100 ms pause condition [$t(22) = -3.70$, $p = 0.001$], and the 200 ms pause condition [$t(22) = -3.93$, $p = 0.001$] (see also Figure 3.5). No other comparison pairs were significant, all $p > 0.005$. In addition, the trend of the Disk speed graph was similar to that of the first experiment, showing an inverted U-shaped curve with the lowest ratios for the slowest and fastest disk speeds (see the supplemental information, Figure S3.2).

Discussion

In this experiment, we again tested the influence of auditory sequences on the judged TTC of an occluded moving object. Compared to Experiment 1, we now used more rhythm variations accompanying the disks in order to more closely investigate a possible critical pause duration. We employed four different pause durations (i.e., pauses ranging from 100 ms until 400 ms) and a No-sound condition. For a large part the results confirmed those of Experiment 1. To begin, the disk speed influenced time estimations of an occluded moving object, showing an inverted U-shape of the JTTC/ATTC ratios as a function of speed of the object. This was similar to Experiment 1. Secondly, we found a significant effect of movement direction, as the objects that moved in the rightward direction were judged to reappear relatively sooner than the objects that moved in the leftward direction. Although we did not observe such an effect in Experiment 1, the finding is consistent with an earlier report of objects moving in the rightward direction being judged as moving faster than objects moving leftward (e.g., Makin, Lawson, Bertamini, & Pickering, 2014). The factor Movement direction was included to have more variety of stimuli, but this factor is not our main concern. Thirdly, the average JTTC/ATTC ratios of all conditions were larger than 1.00. This implies that for each condition, the participants judged the objects to reappear later than they actually would reappear, and the speed was judged to be slower than it actually was. This is in agreement with the results of Experiment 1. Fourthly, and also in line with Experiment 1, we found a significant increase with regard to the JTTC/ATTC ratios between 200 ms and 300 ms, which seems to be a rather critical pause duration in the current experimental setup. Thus, having pause durations longer than 200 ms led to a significant increase in JTTC/ATTC ratios. More specifically, objects accompanied by rhythms with a pause duration larger than 200 ms were judged to reappear later than objects accompanied by rhythms with a 200 ms pause duration or less and objects not accompanied by a sound.

The longer TTC judgments cannot simply be attributed to the accompanying sound sequence per se since there was no difference between the No-sound condition and the sequences with the 100 ms and the 200 ms pause durations. Since the rhythmic structure of a sound sequence seems crucial, we now focus on the role of pause duration versus sound duration that make up the rhythms. That is, in Experiments 1 and 2 we increased the pause duration, while keeping a constant sound duration. Consequently, since there were a higher numbers of sound onsets in the relatively short-pause conditions, the obtained effects could be the result either of differences in the duration of the pauses, or the different number of sound onsets. To disentangle these two possibilities, in Experiment 3 we used a complementary manipulation, namely increasing the sound duration while keeping a constant pause duration.

Experiment 3

In Experiment 3 we performed a complementary manipulation to the ones in Experiments 1 and 2. That is, instead of increasing the pause durations to obtain slower rhythms, here we increased the sound durations to obtain slower rhythms. Hereby we created the same rhythm conditions (i.e., number of sound onsets) as in the previous experiments. If this sound manipulation would lead to results similar to those we obtained in Experiments 1 and 2, this would indicate that rhythm is the critical variable. If on the other hand this sound manipulation did not lead to the same effects as pause manipulation, then this would be evidence that the effects above depend on the duration of the pauses rather than on the rhythm per se.

Methods

Participants

Sixteen participants (11 females) ranging in age between 19 and 27 years (average age 22.88 years, SD = 3.18) participated in the experiment. All participants reported normal hearing, and normal or corrected-to-normal vision. In return, all participants received course credit or money, and informed consent was obtained from each participant before the experiment. This study was approved by the local ethics committee.

Stimuli

We used the same visual stimuli as Experiments 1 and 2, but new auditory stimuli were created. More specifically, four different sound durations were created: 100 ms, 200 ms, 300 ms, and 400 ms, with similar pitch and amplitude as in Experiments 1 and 2. Using these four varied sound durations, and the 100 ms pause duration, we created four rhythms. Note that, with this modulation, the numbers of sound onsets while the object was occluded were the same for Experiments 2 and 3 (cf. Figures 3.4 and 3.6). Consequently, the rhythms (i.e., number of sound onsets) were also the same.

Design

Combining the different rhythm conditions, disk speeds and movement directions, the total number of unique trials was 100: Rhythm (five levels; No-sound, 100 ms sound duration, 200 ms sound duration, 300 ms sound duration, and 400 ms sound duration) × Disk Speed (10 levels; 5.0°/s, 5.5°/s, 6.0°/s, 6.7°/s, 7.5°/s, 8.6°/s, 10.0°/s, 12.0°/s, 15.1°/s, and 20.1°/s) × Movement direction (two levels; leftward and rightward).

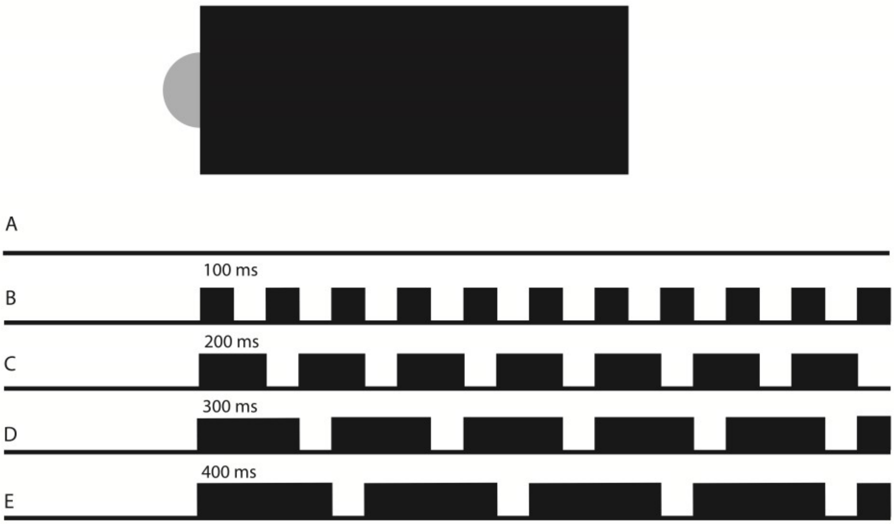

Figure 3.6. Schematic diagram of Experiment 3 showing the auditory and visual stimuli. The auditory sequence starts to play when the center of the object reaches the leading contour of the occluder. Each solid rectangle represents a sound: (A) No-sound condition; (B) 100 ms sounds alternated with 100 ms pauses; (C) 200 ms sounds alternated with 100 ms pauses; (D) 300 ms sounds alternated with 100 ms pauses; (E) 400 ms sounds alternated with 100 ms pauses.

Procedure

The procedure was identical to that of Experiment 2.

Results

The JTTC/ATTC ratios of the five Rhythm conditions were calculated for each participant separately and their means were as follows: No-sound (1.24, SD = 0.21), 100 ms sound (1.24, SD = 0.22), 200 ms sound (1.24, SD = 0.23), 300 ms sound (1.23, SD = 0.21), and 400 ms sound (1.26, SD = 0.21) (Figure 3.7). One-sample *t*-tests showed that the average JTTC/ATTC ratios of all conditions were significantly higher than 1.00: No-sound [$t(15) = 4.56$, $p < 0.001$], 100 ms sound [$t(15) = 4.35$, $p = 0.001$], 200 ms sound [$t(15) = 4.17$, $p = 0.001$], 300 ms sound [$t(15) = 4.44$, $p < 0.001$], and 400 ms sound [$t(15) = 4.81$, $p < 0.001$].

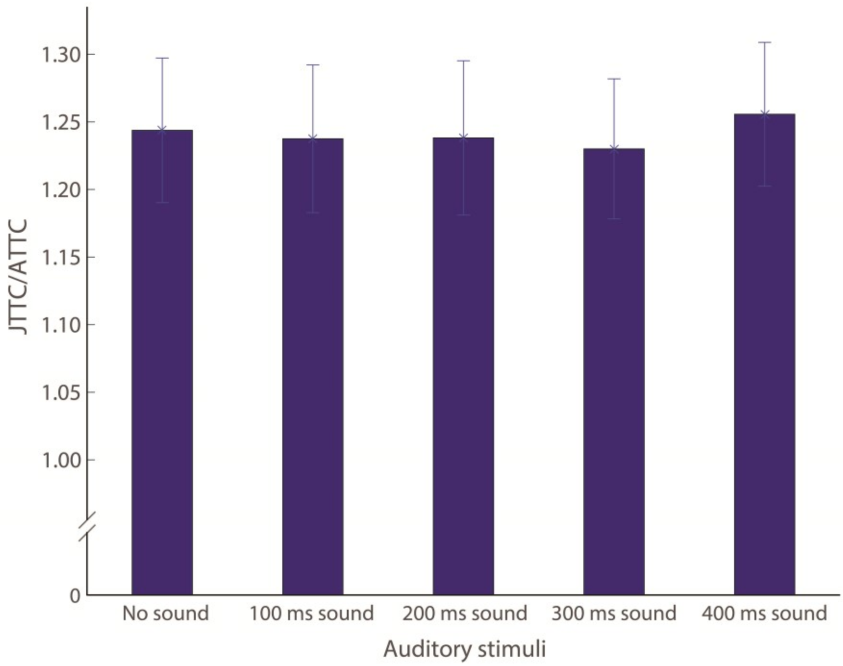

Figure 3.7. Results of Experiment 3. Average ratios between judged time to contact and actual time to contact (JTTC/ATTC ratios). Error bars indicate +/-1 SEM.

A repeated-measures ANOVA was run with Rhythm (five levels), Disk speed (10 levels) and Movement direction (two levels) as the independent factors and the JTTC/ATTC ratio as the dependent variable. Only the factor Disk speed was found to be significant [$F(9,6) = 9.03$, $p = 0.007$], and showed the same trend as in Experiments 1 and 2, an inverted U-shaped graph (see the supplemental information, Figure S3.3).

Discussion

The crucial property that we varied in this third experiment was sound duration. Unlike the results in Experiments 1 and 2, varying the sound durations did not affect the expected TTC of an occluded moving object. Stating it otherwise, TTC judgments thus appear to be more influenced by variations in pause duration than by variations in sound duration, implying that not rhythm or number of sound onsets, but pause duration was the significant factor. In addition, disk speed affected the judged TTC with highest overestimations for middle disk speeds. This result was in line with the results from Experiments 1 and 2.

In Experiments 1 and 2, we found that relatively slow rhythms led to longer TTC judgments of a moving object as compared to relatively fast rhythms. Apparently, the temporal structure, especially the pause duration of this concurrently played auditory sequence, affects the judged TTC. In particular, what we observed was that only pause durations longer than 200 ms lengthened judged TTC, while no effects of varying the sound durations were observed. This observation is potentially important for timing models such as the internal clock model (Treisman, 1963), which assumes that timing perception is based on the auditory frequency (Penton-Voak et al., 1996; Treisman, Faulkner, Naish, & Brogan, 1990; Wearden et al., 2007). Although we did not test perceived duration explicitly, it is plausible to assume that TTC judgments rely at least partially on timing. Since timing experiments usually manipulate pause durations only, it may well be the case that pause duration rather than auditory frequency is the critical variable in those experiments.

To re-phrase our finding, given the same auditory frequency (i.e., number of sound onsets, or rhythm), there is a clear asymmetry in the effect of longer pause durations as compared to the effect of longer sound durations. This asymmetry begs for an explanatory account. We suspect that the auditory sequences with the shorter pauses (and unchanged sound duration) were perceived to be more continuous than the auditory sequences with the longer pauses. In turn, the perceived continuity of an accompanying sound sequence may have influenced the judged TTC. A similar effect on perceived continuity (i.e., auditory grouping) was found in an Event-Related Potentials study (Sussman & Gumenyuk, 2005). In other words, the temporal proximity of individual elements within a sound sequence may play an important role in auditory grouping and this may also influence temporal judgments (see, e.g., Geiser & Gabrieli, 2013; Kuroda, Tomimatsu, Grondin, & Miyazaki, 2016). Thus, when there is weak auditory grouping among the elements of an accompanying sound sequence, perception of amodal movement in turn may be more discontinuous. In the control experiment to be discussed next, we tested the perceived continuity of auditory sequences in which we varied pause duration or sound duration as we did for auditory stimuli in Experiments 1, 2 and 3.

Experiment 4 – Control Experiment

We suggest that relatively long pauses modify TTC judgments because they influence perceived continuity of the accompanying sound, but that this was not the case for the relatively long sound durations. We tested our hypothesis by using a survey to test the influence of variations in pause and sound durations on the perceived continuity. Specifically, we asked participants to judge the perceived continuity of sound sequences, which were varied in either pause or sound duration. We expected that relatively long pause durations would lead to lower perceived continuity than relatively short pause durations. For variations in sound duration, this was not expected. Thus, from our results in Experiments 1, 2 and 3, we expected that longer pause durations would be rated as less continuous, but that longer sound durations would not have such an effect.

Methods

Participants

Thirty-six participants (28 females) ranging in age from 17 to 39 years (average age 22.36 years, SD = 5.85) participated in the experiment. All participants reported normal hearing. Thirty participants received course credits in return for their participation and six participants were volunteers. Informed consent was obtained from each participant before they started the first experimental question. This online survey was approved by the local ethics committee.

Stimuli and Design

The auditory sequences were created with the same procedure as Experiments 1, 2 and 3 but the length of all auditory sequences was limited to three seconds (note that in Experiments 1–3 the sounds were played continuously until participants responded). Similar to the experiments above, there were two types of variations; pause duration and sound duration. More specifically, four different pause/sound durations were created, similar to Experiments 2 and 3: 100 ms, 200 ms, 300 ms, and 400 ms. When sound duration was varied, pause duration was set to 100 ms, and vice versa. In total, there were 24 trials: Pause/Sound Variation (two levels; pause and sound) × Duration (four levels; 100 ms, 200 ms, 300 ms, and 400 ms) × three repetitions.

Procedure

An online experiment was created using the open source LimeSurvey application, version 2.50+ (LimeSurvey GmbH, Hamburg, Germany). Following an informed consent statement, participants received on-screen instructions in which they were asked to rate the perceived continuity of the 24 sound sequences. Each trial started with the sound sequence automatically being played, together with the question “How continuous do you think this sound sequence is? 1 = not continuous at all, and 10 = very continuous" presented on the screen. Thus, participants were asked to judge continuity of the sound sequence on a 10-point Likert scale. Trials could not be skipped, the entire experiment had to be completed in a single session and took approximately 10 minutes to complete.

Results

The average judged continuity of the two Pause/Sound Variation and four Rhythm conditions were calculated for each condition and per participant separately. Two participants were excluded (one participant reported that she had not understood the task's instruction but still completed the survey, and one participant's average responses deviated more than two standard deviations from the group average). The average judged continuity of the two Pause/Sound Variations were as follows: Pause duration (5.93, SD = 2.29) and Sound duration (6.95, SD = 1.55). The average judged continuity of the four Rhythm conditions were as follows: 100 ms duration (6.95, SD = 2.50), 200 ms duration (6.63, SD = 1.72), 300 ms duration (6.35, SD = 1.96), and 400 ms duration (5.82, SD = 2.20).

A repeated-measures ANOVA was run with Pause/Sound Variation (two levels), and Rhythm (four levels) as the independent factors, and average judged continuity as the dependent variable. Both the factor Pause/Sound Variation [$F(1,33) = 19.12$, $p < 0.001$], and Rhythm [$F(3,31) = 3.44$, $p = 0.029$] were found to be significant. The interaction between Pause/Sound Variation and Rhythm [$F(3,31) = 3.81$, $p = 0.020$] was also found to be significant (see Figure 3.8).

To more closely investigate the interaction effect, pairwise t-test ($p < 0.013$, Bonferroni-corrected) comparisons were performed. Pairwise comparisons showed that the 100 ms pause duration was not significantly different from the 100 ms sound duration [$t(33) = -0.07$, $p = 0.947$], the 200 ms pause duration was significantly different from the 200 ms sound duration [$t(33) = -3.09$, $p = 0.004$], the 300 ms pause duration was significantly different from the 300 ms sound duration [$t(33) = -3.19$, $p = 0.003$], and the 400 ms pause duration was significantly different from the 400 ms sound duration [$t(33) = -4.29$, $p < 0.001$].

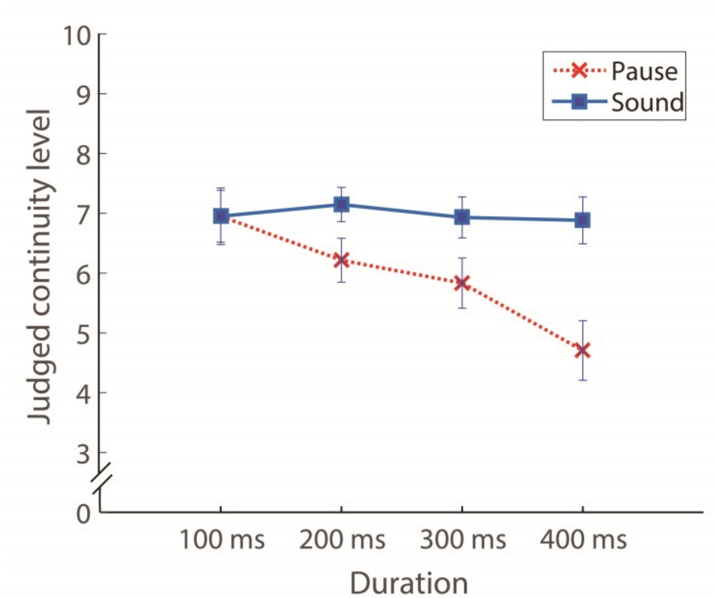

Figure 3.8. Results of Experiment 4. Average judged continuity of pause and sound durations. Error bars indicate +/-1 SEM.

Discussion

The results showed that when participants had to judge perceived continuity of a sound sequence, they tended to judge the continuity based on the changes in pause duration but not the changes in sound duration. That is, variations in sound durations did not lead to changes in perceived continuity, whereas relatively short pause durations between two consecutive sounds led to higher judged continuity than relatively long pause durations. These results are in line with other studies that showed that temporal proximity is a crucial property when judging auditory grouping (Geiser & Gabrieli, 2013; Kuroda et al., 2016). These results may well underlie the results found in the above experiments. The sound sequences with longer pauses appear to be perceived as less continuous, and this in turn may have led to an influence on a simultaneous amodal movement.

General Discussion

The aim of this study was to test the influence of auditory rhythms on the judged TTC of an occluded moving object. An occluded moving object lacks a phenomenological presence (the object is not really seen), but it still has representational properties (Flombaum & Scholl, 2006). We tested this influence by having participants judge the moment the object, without sound or accompanied by a sound sequence, would reappear from behind an occluder.

Overall, the experiments showed that the presence of auditory stimuli modulated the judged TTC of an amodal movement. This is in line with other studies that showed that auditory stimuli can affect expected motion extrapolation and TTC (Chien, Ono, & Watanabe, 2013; DeLucia et al., 2003; DeLucia et al., 2016; Hidaka, Teramoto, Gyoba, & Suzuki, 2010; Hidaka et al., 2015; Hofbauer et al., 2004; Wuerger et al., 2010). Similarly, our results are in line with other multimodal studies that showed that auditory stimuli have influences on the temporal perception of visual stimuli (Burr et al., 2009; Getzmann, 2007; Morein-Zamir, Soto-Faraco, & Kingstone, 2003; Repp & Penel, 2002; Vroomen, Keetels, de Gelder, & Bertelson, 2004).

Based on the results of Experiments 1 and 2, our results show that slower rhythms lead to longer TTC judgments. This confirms our initial hypothesis that longer TTC judgments could be based on slower perceived speed of an occluded moving object, which in turn is based on a slower rhythm. However, pause duration rather than rhythm per se turned out to be critical in judging the speed of a simultaneous occluded moving object. Experiment 3 revealed that variation in sound duration had no effect on perceived speed of an occluded moving disk, while Experiments 1 and 2 showed that comparable rhythms (i.e., same number of sound onsets) with varying pause durations did have effects. Hence, an association of a slow rhythm (i.e., slow alternation) with a slow moving object only holds for increases in pause durations, not for increases in sound durations. As mentioned earlier, this observation may have implications for the related field of time perception, where auditory frequency is thought to have a major impact on perceived duration (Penton-Voak et al., 1996; Treisman et al., 1990; Wearden et al., 2007). Since in this field usually pause durations are manipulated, but not sound durations, it appears likely that asymmetries similar to those reported by us can be found there as well — although not necessarily so as other paradigms are used. Future research should establish whether the asymmetry also holds for other timing tasks.

Experiment 4 hints at a potential reason for finding these differential effects of pause versus sound durations on judged TTC. Sound sequences with long pauses were perceived as less continuous than sound sequences with short pauses, while the variations in sound duration appeared irrelevant. It thus seems plausible that the perceived continuity of the sound sequences affects an amodal processing stage, and therefore affected TTC judgments. The perceived continuity of sounds with short pauses is in line with laws of proximity (Foley et al., 2004; Poynter, 1983; Sussman & Gumenyuk, 2005). Our results, particularly Experiment 4, are also in line with a study of Foley et al. (2004). Their temporal judgment study suggests that an auditory event with short pauses is more likely to be perceived as a single event (i.e., one single chain of sound-pause alternations) and judged to last for a shorter time than the auditory event with longer pauses, which are more likely to be divided into many smaller sub-events and judged to last for a longer time (Foley et al., 2004). Furthermore, the auditory grouping effect that was found in an Event-Related Potentials study (Sussman & Gumenyuk, 2005) is close to the 200–300 ms pause duration that appeared critical also in our Experiments 1 and 2. Note, however, that Sussman and Gumenyuk investigated only auditory stimuli while here both visual and auditory stimuli were being investigated. From our data, grouping appears to be relevant not only in purely auditory settings, but also in the effects of auditory stimuli on amodal perception. Besides our study, Gordon and Rosenblum's (2005) multimodal study also showed the importance of continuity of both visual and auditory stimuli on TTC judgments. That is, they found that the accuracy of the judged arrival time of an ambulance (using movie clips) was higher when both the visual movements and the accompanying sounds were continuous, or when they were alternately presented, than when they both appeared and disappeared simultaneously along the movement trajectory (Gordon & Rosenblum, 2005). Both their and our studies suggest that auditory grouping and perceived continuity can affect perceived amodal movements and TTC judgments.

The auditory stimuli used here comprised sounds that provided no spatial cues with regard to the occluded moving object, i.e., the sound source remained stationary. It is known that spatial co-localisation is important for crossmodal integration of motion in the horizontal plane (e.g., Harrison, Wuerger, & Meyer, 2010; Meyer, Wuerger, Röhrbein, & Zetzsche, 2005). Future research might combine co-localization (similar to the moving sounds in Hofbauer et al., 2004; Wuerger et al., 2010) with the manipulations in the current study. It would be interesting to see whether co-localization would affect the effects we found on TTC measurements.

In this study we restricted our auditory stimuli to base durations of 100 ms. For future research, it would also be interesting to examine a wider range of base durations of pause and sound, to explore how TTC responses are affected. Also, since temporal information is closely linked to the auditory modality (e.g., Getzmann, 2007; Repp & Penel, 2002), while spatial information is more tightly linked to the visual modality (e.g., Battaglia et al., 2003; Witten & Knudsen, 2005), it would be interesting to investigate whether the characteristics of auditory stimuli (e.g., number of sound onsets, pause and sound variations) affect spatial judgments in the same way as temporal judgments. Other auditory settings that would facilitate grouping (e.g., other types of regular intervals, grouping by pitch when using sounds of different pitches, etc.) could be studied as well.

Our results can be considered to be in line with the findings of Hubbard and Courtney (2010) showing that knowledge or high-level processes can build up an association between auditory and visual stimuli. In other words, characteristics of auditory stimuli can be associated with a moving object and influence expected visual movement and location. More specifically, the current findings suggest that the accompanying long pause durations can be associated with slow movements.

In conclusion, this study reveals that without specific auditory localization information, a rhythmic sound sequence accompanying an occluded moving disk can influence time to contact judgments. Specifically, an asymmetric effect between pause and sound durations on TTC judgments was found. We suggest that the perceived discontinuity of a concurrent sound sequence with long pauses can influence the perception of an amodal movement and affect temporal judgments of an expected visual event. Such auditory influences thus may affect expected movements of objects that are obstructed by other objects in everyday life.

Supplemental information

The JTTC/ATTC ratios in each experiment revealed an inverted U-curve as a function of Disk speed. In other words, the overestimation of the TTC was strongest for the middle disk speeds as shown in Figures S3.1-S3.3.

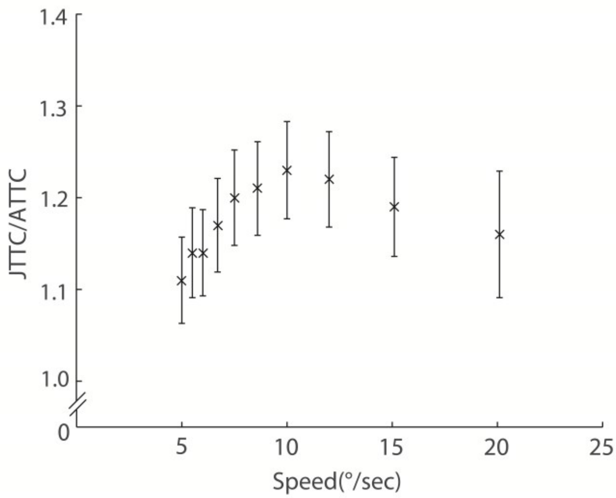

Figure S3.1. Average JTTC/ATTC ratios as a function of Disk speed for Experiment 1. The used Disk speeds were: 5.0°/s, 5.5°/s, 6.0°/s, 6.7°/s, 7.5°/s, 8.6°/s, 10.0°/s, 12.0°/s, 15.1°/s, and 20.1°/s. The error bars indicate +/-1 SEM.

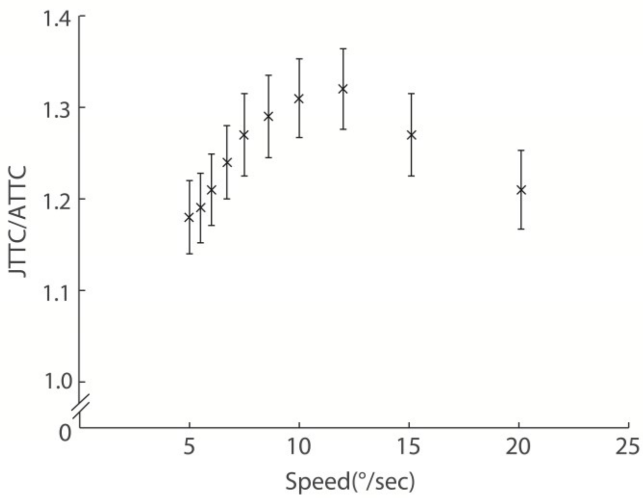

Figure S3.2. Average JTTC/ATTC ratios as a function of Disk speed for Experiment 2. The used Disk speeds were the same as in Experiment 1. The error bars indicate +/-1 SEM.

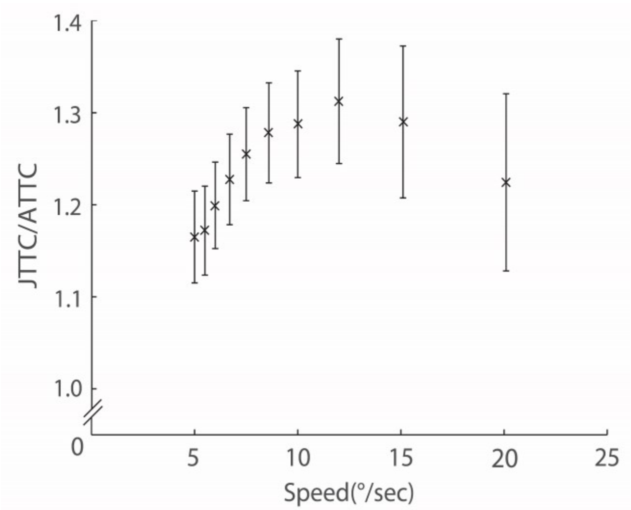

Figure S3.3. Average JTTC/ATTC ratios as a function of Disk speed for Experiment 3. The used Disk speeds were the same as in Experiment 1. The error bars indicate +/-1 SEM.

4

Effects of auditory patterns on judged displacements of an occluded moving object

Based on : Chotsrisuparat, C., Koning, A., Jacobs, R., & van Lier, R. (2018). Effects of auditory patterns on judged displacements of an occluded moving object. Multisensory Research, 31(7), 623-643.

Abstract

Using displays in which a moving disk disappeared behind an occluder, we examined whether an accompanying auditory rhythm influenced the perceived displacement of the disk during occlusion. We manipulated a baseline rhythm, comprising a relatively fast alternation of equal sound and pause durations. We had two different manipulations to create auditory sequences with a slower rhythm: either the pause durations or the sound durations were increased. In a trial, a disk moved at a constant speed, and at a certain point moved behind an occluder during which an auditory rhythm was played. Participants were instructed to track the occluded disk, and judge the expected position of the disk at the moment that the auditory rhythm ended by touching the judged position on a touch screen. We investigated the influence of the auditory rhythm, i.e., ratio of sound to pause duration, and the influence of auditory density, i.e., the number of sound onsets per time unit, on the judged distance. The results showed that the temporal characteristics affected the spatial judgments. Overall, we found that in the current paradigm relatively slow rhythms led to shorter judged distance as compared to relatively fast rhythms for both pause and sound variations. There was no main effect of auditory density on the judged distance of an expected visual event. That is, whereas the speed of the auditory rhythm appears crucial, the number of sound onsets per time unit as such, i.e., the auditory density, appears a much weaker factor.

Introduction

We may use all kinds of visual cues (e.g., object size, motion speed) to estimate visual distances or judge expected positions of moving objects. Such a prediction of a visual movement is called motion extrapolation (e.g., DeLucia & Liddell, 1998; Makin et al., 2008). We do not only extrapolate future motion of visible moving objects, but also in everyday situations in which objects may move in and out of sight, e.g., because of occlusion. The perceptual continuity of an object that disappears behind an occluder and then reappears at the other side of that occluder is known as the Tunnel Effect (cf. Burke, 1952; Flombaum & Scholl, 2006; Flombaum et al., 2008; Michotte, 1950). Since during occlusion the object is amodally present (e.g., Michotte, Thines, & Crabbé, 1964; Michotte et al., 1991), we will refer to such an occluded movement as an 'amodal movement'. In daily life, however, we do not only see moving visual objects but we often simultaneously hear accompanying sounds (e.g., a moving car with its engine sounds). Judgments with regard to future positions of objects can of course be made in both the temporal domain (‘when is an object at a certain spatial location?’) and in the spatial domain (‘where is the object at a certain point in time?’). Here we asked whether concurrent sounds influence spatial expectation of an occluded moving object.

Some recent studies showed that the auditory modality may come into play and affect the expected position of a visual object (e.g., Chien et al., 2013; Getzmann, 2007; Hidaka et al., 2015; Sekuler et al., 1997; Teramoto, Hidaka, Gyoba, & Suzuki, 2010; Teramoto et al., 2012). For example, Chien et al. (2013) found that a transient sound could modulate the expected final position of an occluded moving object. In their experimental setup, a moving object abruptly disappeared from the screen and a transient sound was presented either before or after object disappearance. The results revealed that if the sound was presented before the object disappeared, the object was judged to move a shorter distance than it actually should have moved. Similar to this, Teramoto et al. (2010) also found an influence of an accompanying continuous sound on the expected position of a moving object. In their experimental setup, an object moved horizontally and disappeared from the screen at an unpredictable moment. Simultaneously presented sounds appeared to expand the judged moving distance, depending on the duration of the sounds (Teramoto et al., 2010). The findings above indicate that the presence of a sound that appears at a specific time can affect judged displacements.

Here, we anticipate that the particular rhythmic characteristics of a sound sequence — e.g., an alternation of sounds and pauses, rather than the moment or duration of a sound — may have an influence on expected visual movements (i.e., amodal movements) as well. To further illustrate the link between audition and the mentioned spatial distortions, we briefly introduce the Oppel–Kundt illusion in which visual space seems to be stretched out when additional elements are presented in the same visual space. Figure 4.1 provides an example of the Oppel–Kundt Illusion.

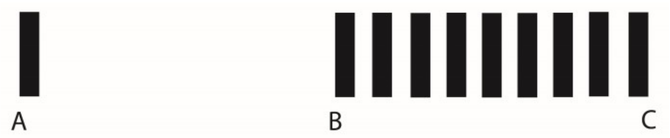

Figure 4.1. Oppel-Kundt Illusion. Although similar in actual distance, the perceived distance between A and B is smaller than the perceived distance between B and C.

One may notice that, in Figure 4.1 the distance between A and B seems much smaller than the distance between B and C, whereas physically the distances are the same. Replacing the visual elements by auditory beeps and the spatial distances with time durations would result in the auditory analogy of the Oppel–Kundt illusion (see Bertulis, Surkys, Bulatov, &

Bielevicius, 2014), also known as the filled duration illusion (and, analogously the Oppel–Kundt illusion could also be named the filled-space illusion). In previous research, it was shown that the judged distances between the first and last visual stimuli in an apparent motion sequence are affected by the number of auditory stimuli, with increases in the number of auditory stimuli leading to larger perceived visual distances (Ichikawa & Masakura, 2005, 2006). This study can be considered as a cross-modal combination of the above phenomena. The filled duration illusion is in line with the prediction from a well-known time perception model, i.e., the internal clock model (Treisman, 1963), namely that the number of stimuli presented within a specific time period should lengthen its perceived duration (Penton-Voak et al., 1996; Treisman et al., 1990; Wearden et al., 2007). According to this model, a higher number of auditory stimuli (i.e., number of sound onsets) within a specific time period should lead participants to perceive that period to last longer compared to a similar time period with a lower number of auditory stimuli or a condition without auditory stimuli. Based on the spatial analogy in the Oppel–Kundt illusion and on the previous cross-modal findings we thus hypothesize that the filled duration illusion will generalize to a judgment of the location of an amodally moving object. Hence, we predict that an amodally moving object that is accompanied by a relatively fast rhythm (i.e., having a higher number of sound onsets) will be judged to move a longer distance than a similar amodally moving object that is accompanied by a relatively slow rhythm.

In the present study, our auditory stimuli consist of sequences of alternating sounds and pauses, and we defined such a sound–pause alternation as ‘rhythm’. In examining the effects of such auditory rhythms on visual movement perception, our research relates to previous research (DeLucia et al., 2003; DeLucia et al., 2016; Hidaka et al., 2010; Hofbauer et al., 2004; Ichikawa & Masakura, 2005, 2006; Wuerger et al., 2010). With the exception of DeLucia *et al*. (2003, 2016), all these studies examined apparent motion rather than real and amodal motion. Another difference with these studies is that they only varied pause durations to change the rhythms, while we varied both sound and pause durations. Furthermore, with the exception of Hidaka et al. (2010), and Ichikawa and Masakura (2005, 2006), all these studies examined time perception (time to contact), while we examine travelled distance. In our previous study (Chotsrisuparat et al., 2017), we found that accompanying rhythmic sound sequences that were presented during the occlusion can affect the time to contact judgment of amodal movements. That is, using a time to contact paradigm we found that the number of sound onsets influenced the perceived duration of an amodal movement, a finding which was compatible with the filled duration illusion (Wearden et al., 2007). More in particular, we found that a relatively fast rhythmic sequence led to shorter judged time to contact than a relatively slow rhythmic sequence, which implies that the occluded moving object was perceived to move at a higher speed. However, quite surprisingly, the modulating effect only occurred when varying pause durations, and not when varying sound durations. Since this finding was achieved with a temporal judgment task, we sought to explore the generality of this finding, by repeating our experiments in different circumstances using a spatial task.

If the temporal judgments of expected visual movements are affected by auditory rhythm, the spatial judgments of those movements are likely to be affected as well. So, one may expect early versus late reappearance judgments that we found in the temporal task (i.e., fast versus slow perceived disk speed) to translate into longer versus shorter displacement judgments in a spatial task, relatively. Alternatively, temporal judgments are known to be more sensitive to auditory information than to visual information (e.g., Burr et al., 2009; Getzmann, 2007; Morein-Zamir et al., 2003; Repp & Penel, 2002; Vroomen et al., 2004), while distance judgments rely more heavily on visual information (Battaglia et al., 2003; King, 2009; Witten & Knudsen, 2005). Hence, it is possible that auditory rhythms will affect judged distances differently compared to the situation where we asked for the judgments of reappearance (Chotsrisuparat et al., 2017). Thus, we envision three likely outcomes for our upcoming experiments in which participants have to judge the position of an amodally moving object that is accompanied by a sound sequence (i.e., sound-pause alternation): 1) we might obtain results consistent with the internal clock model, namely that judged distance travelled by an amodally moving object is related to the number of auditory stimuli (i.e., the number of sound onsets); 2) we might generalize the results of our temporal judgment study (Chotsrisuparat et al., 2017), showing a relationship between the number of auditory stimuli and judged distance, but only when varying pause durations; 3) we might find that auditory rhythms do not have an influence on spatial judgments in the way that they have on temporal judgments. By investigating the effects of auditory rhythms on spatial judgments of amodal movements, we may get a better understanding of how auditory stimuli influence spatiotemporal aspects of visual perception.

In sum, we examined whether auditory characteristics affect spatial judgments. More specifically, in Experiment 1, we investigated the effects of auditory rhythms on amodal movements by varying either sound or pause duration. Using a base duration of 80 ms, the ratio of sound to pause durations could be 1:1 (i.e., 80 ms sound:80 ms pause), 1:2, 2:1, 1:3, and 3:1. In addition to these, we included a no-sound baseline condition. In Experiment 2, we sought to establish an alternative way of increasing the number of sound onsets, namely by additionally using a 40 ms base duration to construct similar rhythmic sequences (i.e., maintaining the same ratios). In both experiments, we explore the influence of auditory characteristics (with both rhythmic and auditory density manipulations) on the estimated distance of an amodally moving object.

Experiment 1

Methods

Participants

Twenty-five right-handed individuals (20 females) ranging in age from 18 to 23 years (average age 19.25 years, SD = 1.36) participated in this experiment. All participants reported normal hearing, and normal or corrected-to-normal vision. All participants received course credits in return for their participation. Informed consent was obtained from each participant before the experiment. This study was approved by the local ethics committee.

Stimuli

The visual displays were presented on a touch screen by the Presentation 17.2 software package. In each trial, a grey disk (0.67° in diameter) moved in a linear horizontal trajectory from left to right on a white background. A black occluding rectangle (height 1.43°) was additionally shown that stretched from the left of the fixation cross to the right side of the monitor, spanning a total of 28.07°. The distance that the grey disk moved before it disappeared behind the occluder was 12.84°. Schematic screenshots of a trial are shown in Figure 4.2. Movie M1 (see supplemental information, online) provides a few examples of experimental trials.

To generate the sound sequences Audacity 2.0.6 was used. The basic sound stimulus was a sinusoidal wave with a frequency of 1500 Hz. An additional sound stimulus was created (a sinusoidal wave with a frequency of 3000 Hz). This additional higher pitched sound was the last note of each

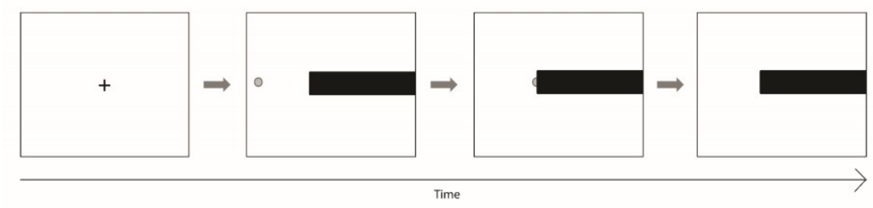

Figure 4.2. A schematic representation of Experiment 1. Four displays of visual stimuli on the touch screen.

auditory sequence in the experiment, to indicate the end of the auditory sequence.

Design

Two basic variations of auditory rhythms were created: pause variations (Block A) and sound variations (Block B), presented in different blocks as shown in Figure 4.3. The sound durations in Block A were kept constant at 80 ms, but the pause duration were varied as follows: 80 ms, 160 ms, and 240 ms. Therefore, the ratios of sound duration to pause duration of Block A were as follows: 1:1, 1:2, and 1:3. In Block B, the pause durations were kept constant at 80 ms, but now the sound durations were varied in a similar way: 80 ms, 160 ms, and 240 ms, resulting in the following ratios of sound duration to pause duration: 1:1, 2:1, and 3:1. We defined reversed ratios (i.e., ratios 1:2 versus 2:1, and ratios 1:3 versus 3:1) to have the same rhythm. Thus, in the following the different rhythms are always expressed as 1: *n*, (e.g., 1:2 or 1:3), while the reversed ratio is accounted for with the variable pause/sound variation. A no-sound condition served as the control condition. See Figure 4.3 for an overview of all variations.

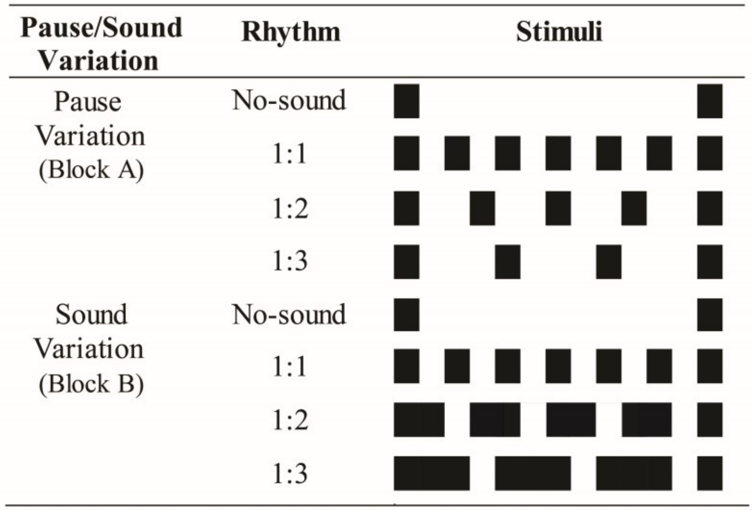

Figure 4.3. Auditory stimuli and block design in Experiment 1. The schematic diagrams of auditory stimuli show the sound sequences that had either varied pause duration (Block A) or sound duration (Block B). The black rectangles represent sounds and the white spaces represent pauses.

To create more variations across experimental trials we additionally varied both initial disk speed and (auditory) sequence length. Disk speed comprised five levels, and sequence length comprised two levels. That is, a sound sequence lasted 1040 ms (short sequence length), or 2000 ms (long sequence length). We considered both disk speed and sequence length as control variables. The total number of trials was as follows: Pause/Sound variation [two levels; pause (Block A) and sound (Block B)] × Rhythm (four levels; no-sound, 1:1, 1:2, and 1:3) (see Figure 4.3) × Disk speed (five levels; 7.80°/s, 9.08°/s, 10.42°/s, 11.68°/s, and 12.84°/s) × Sequence length (two levels; 1040 ms, and 2000 ms) = 80 unique trials.

Procedure

Participants were seated at a distance of approximately 60 cm from the eyes to the touch screen (resolution of 1920 x 1080 pixels, refresh rate 60 Hz). The screen was oriented on its backside mounted in a table, with its screen facing upward. Two loudspeakers were placed on both sides of the touch screen.

The sound intensity was calibrated at 68 decibels. The fixation cross was presented on the screen for one second before the visual stimuli appeared. After the fixation cross disappeared, the disk started moving in the rightward direction. The moment that half of the disk was behind the occluder, a sound sequence started to play depending on the auditory condition. Participants were instructed to track the moving, but occluded, disk. In addition, they were not allowed to touch the screen before the sound sequence of each trial ended. With regard to the response, participants were instructed to touch the screen with the tip of the index finger, at the spot where the disk would be at the moment that the auditory sequence stopped. The end of the sound sequence was indicated by a higher pitched tone.

Sound variations and pause variations were presented in separate blocks. Before starting each block, participants completed four randomly selected practice trials to become familiar with the task. Next, each of the unique 40 trials was presented three times in a random order within each pause/sound block (120 trials per block). The order of the sound variation block and pause variation block was counterbalanced across participants. There were 240 trials in total for the whole experiment. There was a short break after every 30 trials to clean the touch screen and allow the participants to take a brief rest. There was also a break between the sound and the pause variation blocks. The experiment took approximately 40 minutes per participant.

Results

The ratio of the judged distance to the actual distance (referred to as JD/AD ratio from now on) was calculated for each participant and each condition separately and served as the dependent variable. The average JD/AD ratio for each rhythm condition was: no-sound (M = 0.91, SD = 0.15), rhythm 1:1 (M = 0.95, SD = 0.15), rhythm 1:2 (M = 0.94, SD = 0.15), and rhythm 1:3 (M = 0.92, SD = 0.14) (see Figure 4.4). One-sample t-test analyses revealed that the JD/AD ratios of the no-sound [$t(24) = -3.10$, $p = 0.005$], and the rhythm 1:3 [$t(24) = -2.86$, $p = 0.009$] were significantly lower than 1.00, indicating an underestimation of the traversed distance.

A repeated-measures analysis of variance (ANOVA), with the experimental variables Pause/Sound variation (two levels), Rhythm (four levels), and the control variables Sequence length (two levels), and Disk speed (five levels) as independent factors and JD/AD ratio as the dependent variable yielded a significant main effect for the factor Rhythm [$F(3,22) = 7.77$, $p = 0.001$]. The factor Pause/Sound variation was not significant [$F(1,24) = 0.048$, $p = 0.828$].

Regarding the main effect of Rhythm, pairwise t-test ($p < 0.008$, Bonferroni-corrected) comparisons showed that the JD/AD ratio of the no-sound condition was significantly lower than the JD/AD ratio of the rhythm 1:1 condition [$t(24) = -4.04$, $p < 0.001$], and the rhythm 1:2 condition [$t(24) = -3.16$, $p = 0.004$]. The JD/AD ratio of the rhythm 1:1 condition was significantly higher than the JD/AD ratio of the rhythm 1:3 condition [$t(24) = 4.71$, $p < 0.001$]. Also, the JD/AD ratio of the rhythm 1:2 condition was significantly higher than the JD/AD ratio of the rhythm 1:3 condition [$t(24) = 3.93$, $p = 0.001$]. No other comparison pairs were significant, $p > 0.008$. The significant comparisons are shown in Figure 4.4.

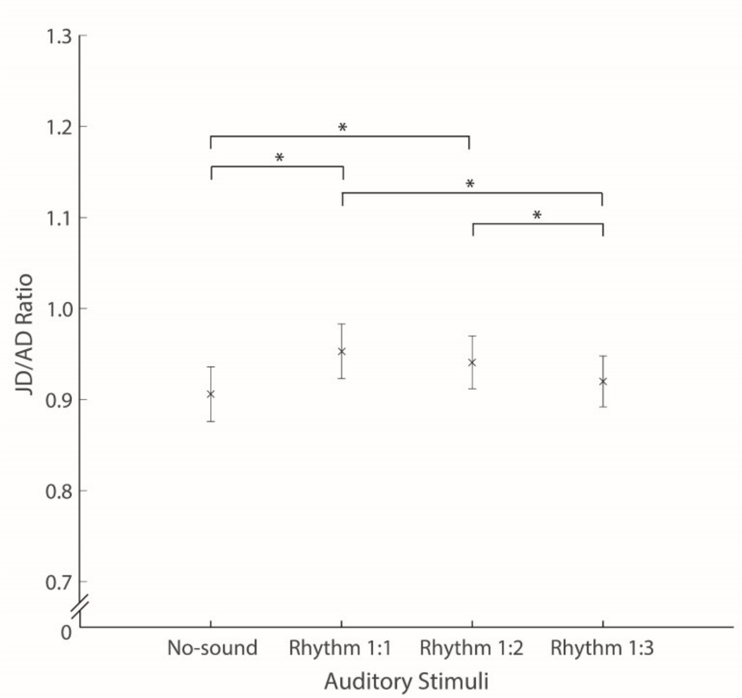

Figure 4.4. The JD/AD ratios as a function of Rhythm of Experiment 1. Error bars indicate +/-1 SEM, and asterisks indicate significant differences (Bonferroni-corrected).

In addition to the main effect of Rhythm, both control variables Sequence length [$F(1,24) = 198.19$, $p < 0.001$], and Disk speed [$F(4,21) = 17.35$, $p < 0.001$] were significant. The average JD/AD ratio of 1040 ms sequence length ($M = 1.07$, SD = 0.17) was higher than the average JD/AD ratio of 2000 ms sequence length ($M = 0.78$, SD = 0.11). One-sample t-tests showed that the average JD/AD ratio of 2000 ms sequence length was significantly lower than 1.00 [$t(24) = -8.17$, $p < 0.001$] while the average JD/AD ratio of 1040 ms sequence length was not different from 1.00 [$t(24) = -1.75$, $p = 0.092$].

For the factor Disk speed, pairwise t-test ($p < 0.005$, Bonferroni-corrected) comparisons showed that the JD/AD ratio of the disk speed 7.80°/s was significantly higher than the JD/AD ratio of the disk speeds 9.08°/s [$t(24) = 4.32$, $p < 0.001$], 10.42°/s [$t(24) = 4.15$, $p < 0.001$], and 11.68°/s [$t(24) = 3.50$, $p = 0.002$] (see Figure 4.5). No other comparison pairs were significant, all $p > 0.005$. JD/AD ratios were higher when the disk speed was relatively slow than when the disk speed was relatively fast.

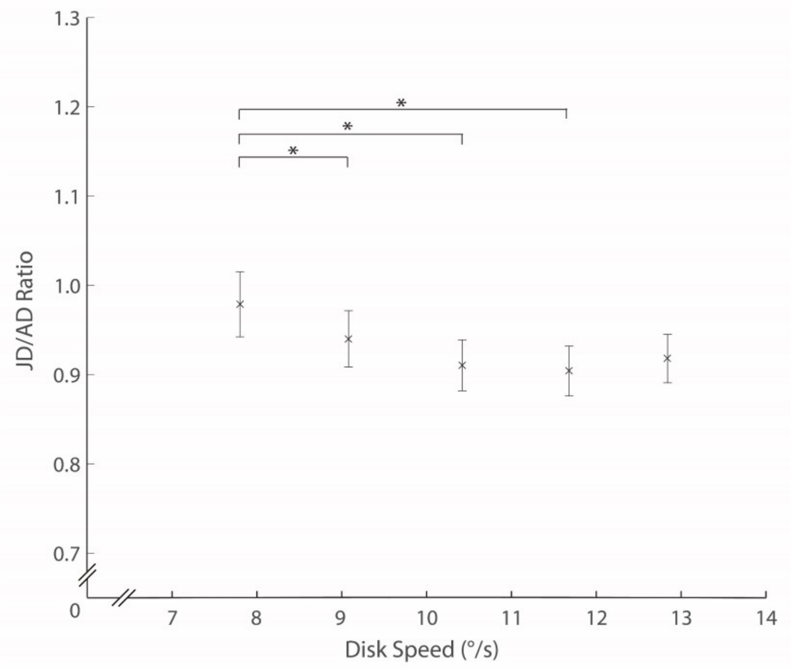

Figure 4.5. The JD/AD ratios as a function of Disk speed of Experiment 1. Error bars indicate +/-1 SEM, and asterisks indicate significant differences (Bonferroni-corrected).

Finally, the interactions between Rhythm and the control variables Sequence length [$F(3,22) = 5.07$, $p = 0.008$], and Disk speed [$F(12,13) = 2.68$, $p = 0.045$] were significant (see Figures 4.6A and 4.6B, respectively). Additionally, the control variables Disk speed and Sequence length revealed a significant interaction [$F(4,21) = 4.64$, $p = 0.008$]. No other interaction effects were significant. Simple effect analyses of Rhythm per level of sequence length ($p < 0.025$, Bonferroni-corrected) revealed significant effects for both 1040 ms sequence length [$F(3,22) = 7.95$, $p = 0.001$] and 2000 ms sequence length [$F(3,22) = 4.37$, $p = 0.015$]. Simple effects analyses of Rhythm per level of disk speed ($p < 0.01$, Bonferroni-corrected) revealed significant effects for the three slowest speeds: disk speed 7.80°/s [$F(3,22) = 5.23$, $p = 0.007$], disk speed 9.08°/s [$F(3,22) = 5.47$, $p = 0.006$], and disk speed 10.42°/s [$F(3,22) = 6.45$, $p = 0.003$].

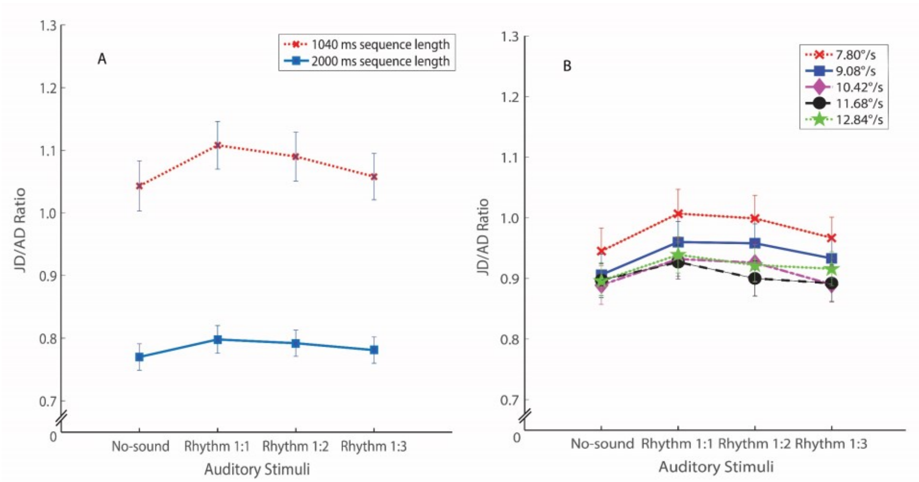

Figure 4.6. The JD/AD ratios as a function of Rhythm and Sequence length (A) of Experiment 1. The JD/AD ratios as a function of Rhythm and Disk speed (B) of Experiment 1. Error bars indicate +/-1 SEM.

Discussion

We investigated whether variations in pause or sound durations, i.e., the rhythm of a sound sequence, affect the spatial judgment of an amodal movement of a disk. Most importantly, we found that both pause and sound variations affect spatial judgment of an occluded moving object. Before dealing with this key finding, we will first discuss a few other experimental results. To begin, the results showed that the average JD/AD ratios of the no-sound, and the rhythm 1:3 were lower than 1.00, indicating underestimations of the distance traversed by the occluded disk. Such underestimations indicate that participants perceived occluded moving objects to move slower when there were no sounds or when they were accompanied by relatively few sounds. Secondly, we found that participants judged the objects to travel further for the short sequence length than for the long sequence length, relative to the actual distance. This agrees with Ihle and Wilsoncroft (1983) who found that the filled duration effect was most pronounced for the relatively short durations. In other words, rhythm affects relatively short durations more than relatively long durations. This strengthens our belief that similar mechanisms underlie the (temporal) filled duration illusion and the effects on judged distance presented in the current paper. We included the factors Sequence length and Disk speed to create more variations of our amodal movements and included these variables in our analysis to control for the variance introduced by them. The interactions of Sequence length and Disk speed with Rhythm in Figure 4.6 reveal that some caution has to be taken on the generalizability of the overall rhythm effect as it appears to be susceptible to the specific experimental settings. Nevertheless, with regard to the control variable Sequence length, the simple effects of Rhythm for the two levels of sequence length appeared significant as well. For the control variable Disk speed, simple effects revealed significant effects of Rhythm for the three slowest speeds.

Altogether, the results support the notion that the judged distance of amodal movement can be influenced by an accompanying rhythmic sound sequence. The overall effect of rhythm suggests that a higher number of sound onsets, i.e., a relatively fast rhythmic sound sequence, leads to longer judged distance of an amodal movement than a lower number of sound onsets, i.e., a relatively slow rhythmic sound sequence, or a no-sound condition. The increase in judged distance that was caused by the higher number of sound onsets was in line with the internal clock model, if we assume that the longer judged distances are based on longer perceived durations. Our findings agree with Ichikawa and Masakura’s results (2005, 2006) and strengthen the notion that the temporal characteristics of auditory stimuli also apply cross-modally, as a spatial analogy to the filled duration illusion. In the present study, our participants estimated distances travelled by judging the final locations of amodally moving objects on a touch screen while participants of Ichikawa and Masakura’s studies (2005, 2006) estimated distances of apparent motion by reporting them verbally. Both our and Ichikawa and Masakura’s studies found similar influences of the number of sounds on judged distances. Hence, whether the judgment was verbal or haptic did not appear to matter.

For our experimental design, there was an unavoidable association between rhythm and the number of sound onsets. That is, the relatively fast rhythms always have a higher number of sound onsets as compared to the relatively slow rhythms. Therefore, the effect of rhythms on judged distance may have come from the different numbers of sound onsets across the different rhythms. In order to scrutinize the effect of number of sound onsets on spatial judgment, we chose to add another manipulation of the number of sound onsets, namely by manipulating sound density. Therefore, in the next experiment, we increased the number of sound onsets by also shortening the base duration. We refer to this manipulation as ‘auditory density’, with sound sequences using 80 ms as the base duration being the ‘low density’ condition and sound sequences using 40 ms as the base duration being the ‘high density’ condition. Thus, the next experiment was set up to examine the influence of these two manipulations of rhythm and auditory density on spatial judgment of amodal movements.

Experiment 2

The results of Experiment 1 were in line with the internal clock model, with more sound onsets leading to longer judged displacements of amodal movements. In Experiment 2, besides the variable number of sound onsets by varying rhythms, we now used a different way to increase the number of sound onsets per time unit by shortening the base duration (i.e., increasing auditory density), in order to observe their effects on judged distance. In this way, the number of sound onsets of the high density blocks were higher than the number of sound onsets of the low density blocks, while the rhythms (i.e., the ratio of alternating sounds and pauses) were equal for both auditory density blocks. We tested whether the judged distance varied with the auditory density, the rhythm or both factors.

Methods

Participants

Twenty-five right-handed individuals (17 females) ranging in age from 18 to 27 years (average age 20.21 years, SD = 1.96) participated in this experiment. All participants reported normal hearing, and normal or corrected-to-normal vision. They all received course credits in return for their participation. Informed consent was obtained from each participant before the experiment. The study was approved by the local ethics committee.

Stimuli

The visual displays were the same as in Experiment 1. For the auditory stimuli, a broader rhythmic range was used. More specifically, the auditory sequences were designed as follows: the 80 ms sounds were alternated with 80, 240, or 400 ms pauses, and the 40 ms sounds were alternated with 40, 120, or 200 ms pauses. In addition, the two sound variation blocks were designed as follows: the 80 ms pauses were alternated with 80, 240, or 400 ms sounds, and the 40 ms pauses were alternated with 40, 120, or 200 ms sounds.

Design

The total number of trials was as follows: Pause/Sound variation (two levels; pause, and sound) × Auditory density (two levels; high, and low) × Rhythm (four levels; no-sound, 1:1, 1:3, and 1:5) × Disk speed (five levels; 7.80°/s, 9.08°/s, 10.42°/s, 11.68°/s, and 12.84°/s) × Sequence length (two levels; 1040 ms, and 2000 ms) = 160 unique trials. There were four blocks: block A and block B were the low-density blocks, and block C and block D were the high-density blocks. Blocks A and C comprised pause variations, whereas blocks B and D comprised sound variations. Hence, in block A, the 80 ms sounds alternated with 80, 240, or 400 ms pauses, whereas in block B the 80 ms pauses alternated with 80, 240, or 400 ms sounds. Similarly, in block C, the 40 ms sounds alternated with 40, 120, or 200 ms pauses, whereas in block D the 40 ms pauses alternated with 40, 120, or 200 ms sounds. Note that according to our definition of a rhythm, the rhythms of blocks A, B, C, and D are all similar, disregarding different densities (blocks A and B versus C and D): no-sound, 1:1, 1:3, and 1:5. In Figure 4.7, the auditory stimuli of the four blocks are presented.

Procedure

The procedure was the same as that of Experiment 1 except for the following. Firstly, participants completed a set of five random practice trials before starting the high density blocks, and before starting the low density blocks to become familiar with the task. Secondly, the presentation of the four blocks was counterbalanced across participants. Half of the participants started with the low-density blocks, while the rest started with the high-density blocks. In addition, half of the participants started with

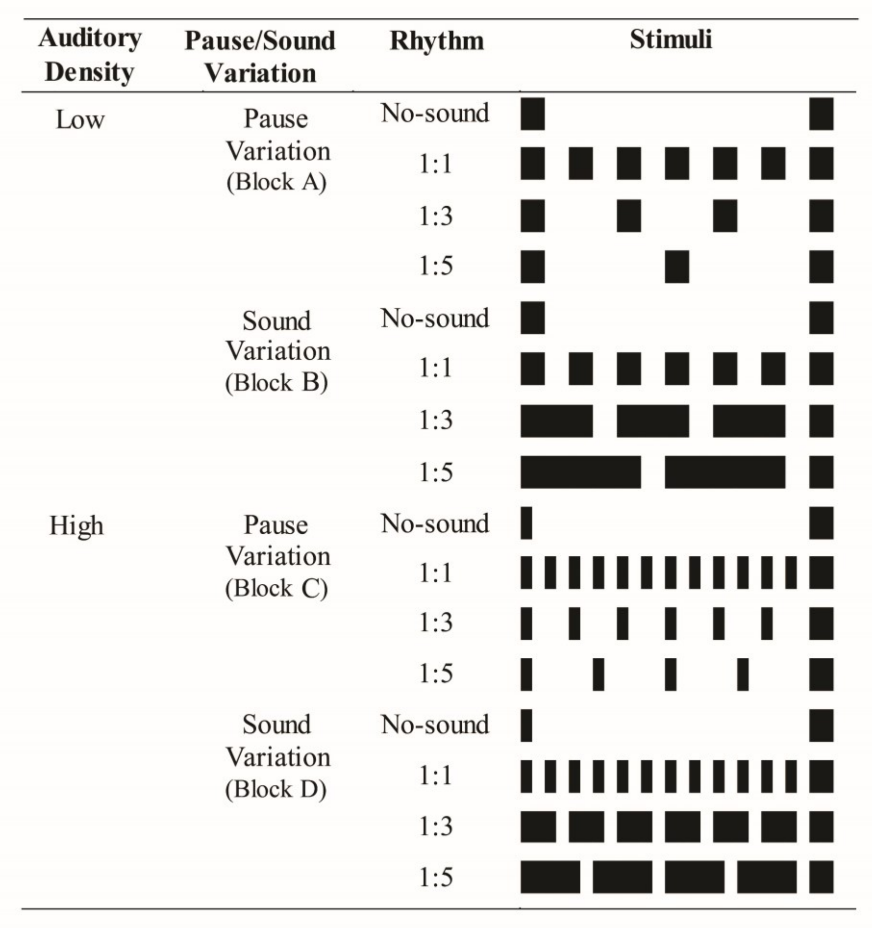

Figure 4.7. Auditory stimuli and block design in Experiment 2. The schematic diagrams of auditory stimuli show the sound sequences that had either varied pause duration (Block A and Block C) or sound duration (Block B and Block D). The black rectangles represent sounds and the white spaces represent pauses.

the pause variation blocks, while the other half started with the sound variation blocks. Next, each of the unique 40 trials within each block was presented two times in a random order (80 trials per block). There were 320 trials in total for the whole experiment. Third, there was a short break after every 40 trials (to allow the participants to take a brief rest and to clean the touch screen), and the whole experiment took approximately 50 minutes to complete.

Results

The JD/AD ratios were calculated for each participant and each condition separately and served as the dependent variable. One participant whose total average JD/AD ratio was more than 2 SDs from the overall average across all participants was excluded from the analysis. For the low-density block, the average JD/AD ratios for each condition were: no-sound (M = 1.07, SD = 0.34), rhythm 1:1 (M = 1.08, SD = 0.30), rhythm 1:3 (M = 1.06, SD = 0.30), and rhythm 1:5 (M = 1.03, SD = 0.31). For the high-density block, the average JD/AD ratios for each condition were: no-sound (M = 1.08, SD = 0.36), rhythm 1:1 (M = 1.10, SD = 0.32), rhythm 1:3 (M = 1.09, SD = 0.33), and rhythm 1:5 (M = 1.07, SD = 0.32). One-sample t-test analyses showed no significant deviations of JD/AD ratios from 1.00 [$p > 0.05$] for all conditions, indicating that there were no systematic overestimations or underestimations of the judged distance.

A repeated-measures analysis of variance (ANOVA) was performed with the experimental variables Auditory density (two levels), Pause/Sound variation (two levels), Rhythm (four levels), and the control variables Sequence length (two levels), and Disk speed (five levels) as independent factors and JD/AD ratio as the dependent variable. There was a significant main effect for Rhythm [$F(3,21) = 9.26$, $p < 0.001$]. Pairwise t-test ($p < 0.008$, Bonferroni-corrected) comparisons showed that JD/AD ratio of the rhythm 1:1 was significantly higher than the JD/AD ratio of rhythm 1:5

[$t(23) = 4.11$, $p < 0.001$]. In addition, the JD/AD ratio of the rhythm 1:3 was significantly higher than the JD/AD ratio of the rhythm 1:5 [$t(23) = 4.83$, $p < 0.001$] (see Figure 4.8). No other comparison pairs were significant, $p > 0.008$. There was a three-way interaction of Rhythm, Pause/Sound variation, and Disk speed [$F(12,12) = 2.83$, $p = 0.042$] (for the graphs, see the supplemental information, Figure S4.1).

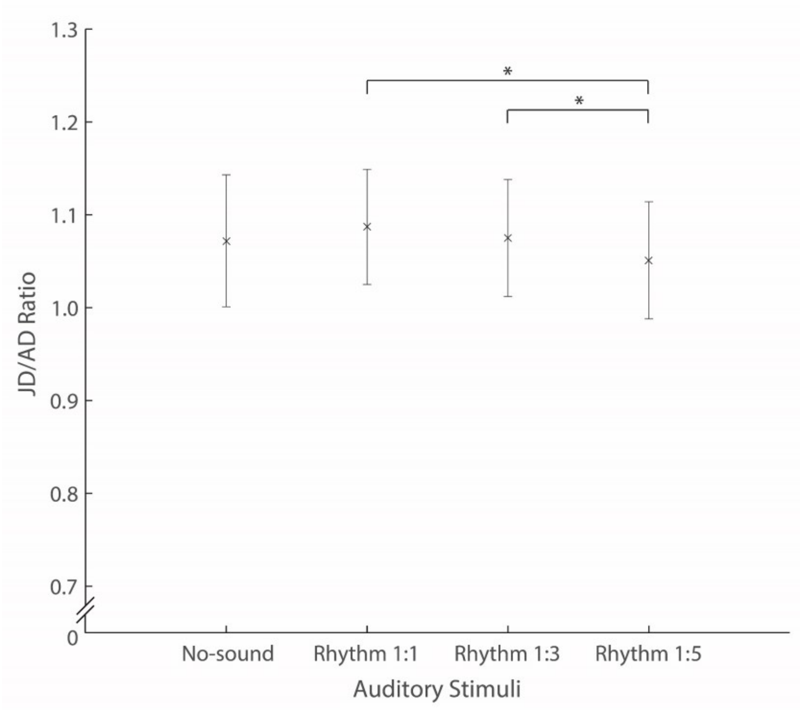

Figure 4.8. The JD/AD ratios as a function of Rhythm of Experiment 2. Error bars indicate +/-1 SEM, and asterisks indicate significant differences (Bonferroni-corrected).

The factors Auditory density [$F(1,23) = 0.74$, $p = 0.398$] and Pause/Sound variation [$F(1,23) = 2.98$, $p = 0.098$] were not significant. Although no main effect of the Auditory density variable was found, an interaction effect between Auditory density and Disk speed [$F(4,20) = 3.79$, $p = 0.019$] was significant. Figure 4.9 reveals the effects of the different disk speeds and auditory densities on the JD/AD ratios. To further investigate the interaction effect we applied post-hoc *t*-tests to the two relevant auditory density levels within each level of the control factor Disk speed. It turned out that for all five levels of disk speed, there was no significant difference between the two auditory density levels (all *p*'s > 0.05). That is, for a given disk speed, auditory density has no differential effect.

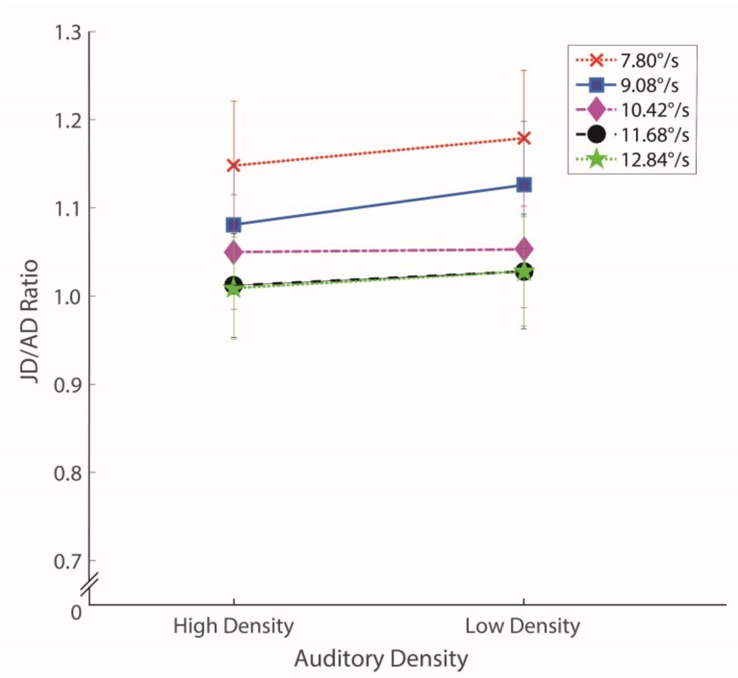

Figure 4.9. The JD/AD ratios as a function of Auditory density and Disk speed of Experiment 2. Error bars indicate +/-1 SEM.

Furthermore, there were significant effects for the control variables Sequence length [$F(1,23) = 99.25$, $p < 0.001$], and Disk speed [$F(4,20) = 9.61$, $p < 0.001$]. For Sequence length, the average JD/AD ratios were: 1040 ms sequence length ($M = 1.26$, SD = 0.40), and 2000 ms sequence length ($M = 0.89$, SD = 0.24). One-sample t-tests showed that the average JD/AD ratio of 1040 ms sequence length was significantly higher than 1.00 [$t(23) = 3.18$, $p = 0.004$] while the average JD/AD ratio of 2000 ms sequence length was significantly lower than 1.00 [$t(23) = -2.32$, $p < 0.030$]. In addition, for the control factor Disk speed most pairwise comparisons were significant ($p < 0.005$, Bonferroni-corrected), except for 10.42°/s vs. 11.68°/s and 11.68°/s vs. 12.84°/s. In addition, there was also a three-way interaction of Auditory density, Disk speed and Sequence length [$F(4, 20) = 3.92$, $p = 0.016$] (for the graphs, see the supplemental information, Figure S4.2).

Discussion

The results of this second experiment show that the average JD/AD ratio of all rhythm conditions were not different from 1.00. The results do reveal a main effect of Rhythm but no main effect of Auditory density of the sound sequences on the spatial judgments. As other effects of Rhythm and Auditory density are also different (i.e., Auditory density interacts with Disk speed, while Rhythm does not), the mere number of sound onsets cannot be the only determining factor in judging the expected location. For rhythm, the results were similar to those of Experiment 1. That is, participants judged relatively shorter distances for the occluded moving object when it was accompanied by slow rhythms as compared to fast rhythm. Note that the relatively slow rhythms led to shorter judged distances of occluded moving objects for both sound and pause variations. The effect of rhythm for both sound and pause variations might strengthen the idea that the number of sound onsets is responsible for these effects, as predicted by the internal clock model. However, other results ask for a more complicated explanatory account. First of all, in contrast to Rhythm, there was no main effect of the newly introduced factor Auditory density. So, an explanatory account based on the mere number of sound onsets is untenable. In addition, various interactions warrant more caution. For example, although the main effect of Rhythm stands out (like in Experiment 1), the three-way interaction of Rhythm, Pause/Sound variation and Disk speed reveals that the findings cannot be straightforwardly generalized across all speeds. In addition, the two-way interaction effect between Auditory density and Disk speed, and the three-way interaction of Auditory density, Disk speed and Sequence length reveal a more subtle effect of auditory density.

As in Experiment 1, there were main effects for the variable Sequence length and Disk speed. With regard to the main effect of the control variable Disk speed, we speculate that the differentially judged distances may be brought about by attention as it is known to play a role in multimodal integration (Macaluso et al., 2016). When there is multisensory information from vision and audition, attention could be differentially allocated to visual and auditory stimuli (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). For example, an object tracking study by Holcombe and Chen (2012) demonstrated that faster moving objects require more attention than slower moving objects. Given that moving objects are also attended when they are temporarily occluded (Flombaum et al., 2008), participants in our experiments may have deployed varying levels of attention to the occluded disk, depending on its speed. The available resources could then be allocated to the auditory modality, away from the more task relevant visual modality, which in turn might have translated into differentially judged distances.

As mentioned, we added the control variables Sequence length and Disk speed to have more variability in the task and to have different actual distances of the amodal movements. With regard to the variables that relate to the relevant auditory characteristics (i.e., Rhythm, Pause/Sound variation, Auditory density), the main effect of Rhythm stands out. However, the interactions show that the specific settings used here to create differences in actual distances, play a role as well. Whatever the underlying mechanism might be, the results show that the influence of sound on spatial judgments does not simply depend on the number of sound onsets.

General Discussion

The aim of this study was to test the influence of auditory characteristics on the judged distance (i.e., distance travelled) of an occluded moving object. We tested the judged distance by having participants manually indicate the location of an occluded moving object on a touch screen at a moment that an accompanying sound sequence stopped playing.

In both experiments, we found that the judged distances of amodal movements were influenced by the rhythm (i.e., ratio of alternating sounds and pauses). The relatively slow rhythms (e.g., the rhythm 1:3, and the rhythm 1:5) led people to judge the occluded moving object to travel a shorter distance than the relatively fast rhythms (e.g., the rhythm 1:1 and the rhythm 1:2). According to the internal clock model, the smaller number of sound onsets that were presented within the relatively slow rhythmic sound sequence should lead to a shorter perceived duration as compared to the higher number of sound onsets within the relatively fast rhythmic sound sequence. We presumed that such shorter perceived durations would also lead to shorter distance judgments. Hence, the rhythm manipulations yielded results that are predicted by the internal clock model (e.g., Penton-Voak et al., 1996; Wearden et al., 2007).

In Experiment 2, we added a higher auditory density (i.e., using a 40 ms base duration, besides the 80 ms base duration) to increase the number of sound onsets compared to Experiment 1. We kept the same rhythm manipulations for both the high and the low density blocks. Based on the internal clock model, one would expect that a larger number of sound onsets of the stimuli in the high density block would lead to longer judged distances of the occluded moving objects than a smaller number of sound onsets of the stimuli in the low density block. Results revealed that the effects of auditory density in Experiment 2 were much more subtle as compared to the effects of rhythm, revealing no main effect of Auditory density and an interaction with Disk speed — although for each individual speed level there was no difference between low and high density. These results indicate that distance judgments are not simply determined by the number of sound onsets, as would be predicted by the internal clock model (e.g., Wearden et al., 2007). Rather, the auditory characteristics of the sound sequence appear to be more important. From the current diverging effects of rhythm and auditory density, we believe that further research on auditory influences in time perception should, besides frequency, also be concerned with other characteristics of auditory stimuli.

In this study, we found no difference between sound and pause manipulations. Both affected *spatial judgment* of amodal movements. In our previous study on *temporal judgment* (Chotsrisuparat et al., 2017), only the pause variations affected the temporal judgments. That is, longer pause durations led to later judged reappearances than the relatively short pause durations, while variations in sound durations had no such effect. In our previous study, we suggested that the larger perceived auditory discontinuity in the sequences with longer pause durations, due to auditory grouping (Sussman & Gumenyuk, 2005), caused the differential effects. It is very well possible that such (temporal) grouping effects have the stronger influences on temporal judgments as compared to spatial judgments, although it should be noted that other paradigmatic differences between the experiments (such as the tone that indicated the end of the movement in the current paradigm), might also underlie the differences.

Now that we found parallels between the temporal filled duration effect and the spatial distance judgments, it would be interesting to look for other parallels in future research. For example, regular sounds tend to be perceived as lasting longer than irregular sounds (Horr & Di Luca, 2014). Hence, we would predict that a disk accompanied by a regular sound sequence would be perceived as moving a longer distance than a disk that is accompanied by an irregular sound sequence, even if both sequences have the same number of actual sound onsets. Other lines of research could also include effect of eye movements as they may have an influence on spatial judgments as well (see, for example, Kerzel, 2000, 2006).

All in all, it can be said that auditory characteristics can play a modulatory role in a spatial task. In this study, we investigated the effects of rhythm and auditory density when judging the traveled distance of an occluded object. Following the experimental results, we conclude that the auditory rhythm influences judged distance of an expected visual event and such judged distance does not simply rely on the number of sound onsets but that they are the result of more subtle audiovisual interactions.

Supplemental information

Experiment 2

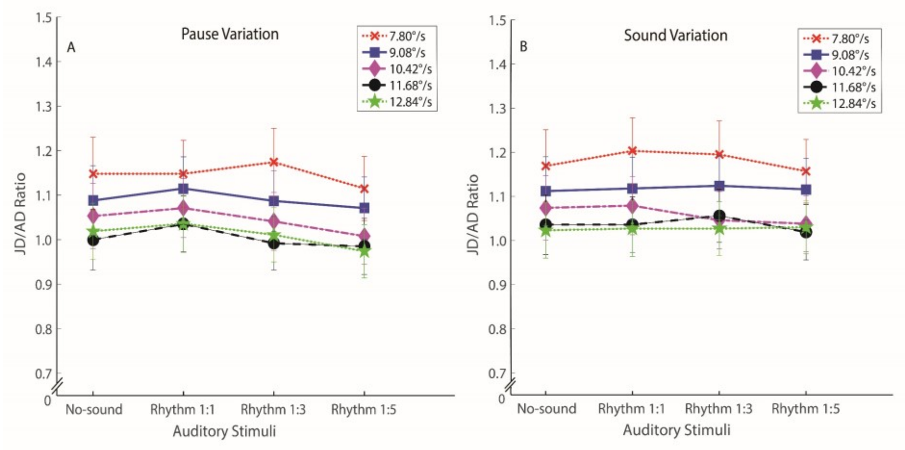

Figure S4.1. The JD/AD ratios as a function of Rhythm, Disk speed and Pause/Sound variation of Experiment 2. Error bars indicate +/-1 SEM.

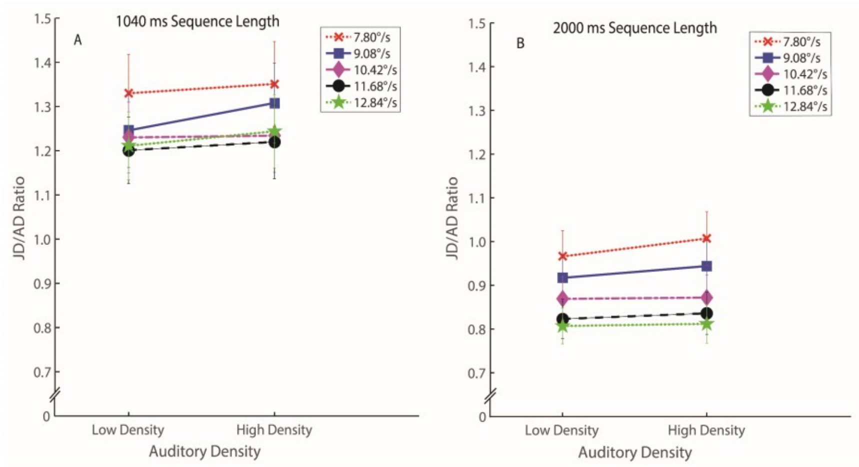

Figure S4.2. The JD/AD ratios as a function of Auditory density, Disk speed and Sequence length of Experiment 2. Error bars indicate +/-1 SEM.

5

Discussion and Summary

The main goal of this thesis has been to investigate time perception of specific visual events. Particularly we investigated spatiotemporal judgments related to the ‘Tunnel effect’. Using both unimodal and multimodal approaches, we have shown that judged time and distance of amodal movements could be influenced by various factors not only by the visual, but also by the auditory modality. Here, we discuss our main findings, the implications of our results, and reflect on possible future research.

Perceived timing of an occluded moving object

Humans have learned in their early life that moving objects may temporarily disappear behind other objects, yet still persist (S. P. Johnson et al., 2003; Rosander & von Hofsten, 2004; van der Meer, 1994). In addition, we have certain expectancies with regard to the time interval after which those objects would reappear. When a moving object is occluded during a part of its trajectory this has been referred to as amodal movement. Here, we explored time perception of a moving object during both amodal movement and during a ‘non-occlusion’ event (i.e., the object remained visible). Judging the timing of an event in case of amodal movement as compared to non-occluded movement led to time compression, but the question arose whether visibility per se or whether differential eye movements might have caused this compression. The results showed that saccade instructions can compress perceived duration as compared to pursuit instructions.

Remarkably, our findings in Chapter 2 revealed that the smaller occluder led to larger time compression than the longer occluder. Previous studies revealed that spatiotemporal continuity of amodal movement is vital for the perception of persistence of an occluded moving object (Flombaum et al., 2004; Flombaum & Scholl, 2006; Flombaum et al., 2009; Yi et al., 2008). With regard to amodal movements, the perceived continuity could have affected perceived duration. Burke (1952) already revealed that the length of an occluder can affect perceived continuity of an occluded object. The longer the occluders, the lower the perceived continuity of the movement as judged by participants. The perceived duration of an occluded moving object behind a relatively long occluder was overestimated (i.e., perceived duration was judged to last longer than actual duration) as compared to a relatively short occluder. Some participants in Burke (1952)'s study even reported that they perceived a discontinuous movement (e.g., they perceived the motion to temporarily pause behind the occluder). Our findings are in line with the findings of Burke. So, time judgments might be modulated by various effects. Saccades tend to compress time intervals whereas the length of the occluder may work in the opposite direction, presumably due to the fact that for long occluders the fixation and waiting time after the saccade is longer. Note that the perceived continuity hypothesis also agrees with the cross-modal study in this thesis Chapter 3.

The results in Chapter 2 revealed that the perceived duration, as a deviation from the actual speed, depended on speed; findings that were in line with previous studies (Brown, 1995; Fortin & Rousseau, 1998). For example, participants judged duration at higher speeds to last relatively longer compared to the actual duration. The effect of speed that we found in our rating task followed Vierordt's law (Woodrow, 1951) while the effect of speed on time to contact (TTC) judgments in Chapter 3 did not follow this law. Participants overestimated TTC for all speeds, while the medium speeds were overestimated more than the slowest and the fastest speeds. Recent results of Baurès, Maquestiaux, DeLucia, Defer, and Prigent (2018) are in line with our TTC judgments in that they also found an overestimation of TTC judgments for all speeds. We suggest that the effect of speed on temporal judgments may depend on the particular time estimation methods as well. Note that care should be taken here as other conditions also differed between the Chapters 2 and 3, such as the speed range or sound conditions. However, as the speed range in Chapter 2 encompasses the speed range in Chapter 3, the speed range as such would not be a sufficient explanatory account.

The influence of rhythm and auditory grouping on perceived continuity of an ongoing event

The results in Chapter 3 showed that TTC judgments of amodal movements can be differentially affected by auditory rhythms, particularly when the durations of the pause intervals in the rhythm were varied. We reasoned that such influences might have been modulated by auditory grouping. The closer auditory stimuli are presented to each other, i.e., the closer they are in terms of temporal proximity, and the stronger they are grouped perceptually (Friberg & Sundberg, 1995; ten Hoopen, Miyauchi, & Nakajima, 2008). More specifically, the control experiment in Chapter 3 showed that the pause duration between two consecutive sounds is important for perceived continuity, while there was no effect of sound duration on perceived continuity when the pause was kept constant. With that, the results in Chapter 3 were in line with the effect of perceived continuity as shown in various studies in which temporal proximity plays a vital role in grouping (Geiser & Gabrieli, 2013; Handel & Lawson, 1983; Sussman & Gumenyuk, 2005). Furthermore, various studies found that participants perceive a sequence of regular and identical sounds as groups of sounds (Bolton, 1894; ten Hoopen et al., 2008; van Noorden & Moelants, 1999). Regular sounds were less likely to be grouped together when the tempo of sound sequences was slow (i.e., larger interstimulus interval) (ten Hoopen et al., 2008).

Besides the unimodal studies mentioned here that showed effects of auditory rhythm on an ongoing auditory event, a study of Wang, Guo, Bao, and Chen (2015) revealed an effect of auditory rhythm on a concurrent visual event. In that study, it was shown that the presentation of sounds affected visual apparent motion (in the so-called Ternus display), depending on specific sound and pause durations. Our study on the effect of rhythm and the differential effect of pause and sound durations on time to contact judgments connects with the above phenomena. Note that a recent unimodal study of Chang and Jazayeri (2018) also revealed that concurrent temporal information (i.e., a flash that was presented during occlusion) influenced time to contact judgments. To summarize, the temporal structure of auditory sequence i.e., auditory grouping appears to cross-modally affect time perception of an ongoing visual event, particularly pause duration of rhythmic auditory sequences appears to influence perceived continuity of an ongoing event.

Filled duration illusion and the spatial analogy

When seeing moving objects, information is processed that is related to both time and spatial location. The influence of rhythm on temporal judgments in Chapter 3 led us to the next question regarding the effect in spatial domain. In Chapter 3, participants judged time to contact i.e., they judge the end of an ongoing event (under various sound conditions). In contrast, in the experiments discussed in Chapter 4 participants judged the distance that an object moved at the moment that an auditory sequence ended. That is, the judged distance of an occluded moving object could be modulated by the perceived duration of a rhythmic auditory sequence. The results of Chapter 4 showed that relatively fast rhythms led to longer judged distance of occluded moving objects as compared to the relatively slow rhythms. The results were in line with the filled duration illusion, which states that an auditory sequence with a high frequency of sound onsets leads to longer perceived duration than a sequence with a rather low frequency of such onsets or no sound at all (Penton-Voak et al., 1996; Repp & Bruttomesso, 2009; Wearden et al., 2007). Remarkably, both pause and sound variations affected the spatial judgments in Chapter 4 while only pause variation affected the TTC judgment in Chapter 3. In analogy to the Oppel-Kundt illusion (see Bertulis et al., 2014), we predicted a dominant influence of just the number of sound onsets (which is equal for both pause and sound variation) on the spatial judgments. However, our second experiment in Chapter 4 revealed that auditory density (i.e., the number of sound onsets per unit of time) had only a subtle effect on judged distance. In contrast, rhythm appeared to have a clear influence on spatial judgment (with about equal effects for pause and sound variation). The discrepancies between the temporal study in Chapter 3 and the spatial study in Chapter 4 may then relate to the different experimental paradigms. For example, TTC judgments required a prompt response, while in the spatial judgment task, such a prompt response was not necessary. We speculate that auditory grouping effects and continuity effects could just be less influential when participants have more time to respond.

Some consequences for existing models

According to the internal clock model (Treisman, 1963) and the attentional gate model (Zakay & Block, 1995), an interval that is filled with a higher number of stimuli leads to a higher pulse rate of the pacemaker and would lead to a longer perceived duration than an interval that is filled with a lower frequency of stimuli or an empty interval (Penton-Voak et al., 1996; Wearden et al., 2007). Thus, a relatively fast rhythm would accelerate the pacemaker's rate more than a relatively slow rhythm or no-sound. Our results on the pause and sound variations in the spatiotemporal tasks in Chapters 3 and 4 raised concerns related to both the internal clock model and the attentional gate model. That is, the differential effect of pause versus sound duration with the same number of sound onsets on the temporal judgments in Chapter 3 suggested that the number of stimuli is not the only factor that can modify the pacemaker rate, but also the rhythmic pattern. Also, the results of auditory density in Experiment 2 of Chapter 4 showed that the number of sound onsets was not of crucial influence. Therefore, both our temporal and spatial judgment results revealed that the internal clock model and also the later developed attentional gate model seem to fall short as in their discussed forms they appear not to be able to account for our findings. In the next section we suggest a way to implement this is by combining aspects of the attentional gate model with the contextual change model.

The contextual change model states that a higher number of changes is perceived to last longer than a lower number of changes (Block 1990, 1992). That is, a visual event that is composed of many small movements would be perceived to last longer than a visual event of a single continuous motion, even if the total durations of both are equal. In the first section of this chapter, we suggested that the longer waiting time i.e., a larger temporal separation in the long occluder condition in the saccade block may have led to less perceived continuity of a motion as compared to the shorter waiting time i.e., a shorter temporal separation of the short occluder condition. The effect of the occluder length in Chapter 2 and the pause effects of auditory stimuli in the Chapter 3, appear to be in a similar direction, i.e., increment of duration. Note that both conditions deal with a reduction of perceived continuity. In Chapter 4, we found that both pause duration and sound duration affected perceived distance. Recent studies (Hasuo, Nakajima, & Hirose, 2011; Hasuo, Nakajima, Osawa, & Fujishima, 2012) also showed that lengthening of sound duration and inter onset interval (i.e., pause duration) can lengthen perceived duration. Note, however, that these studies (Hasuo et al., 2011; Hasuo et al., 2012) used the method of points of subjective equality (PSEs) with only two to three sounds while we used longer sound sequences that were composed of a higher number of sounds and different judgments. Overall, the mentioned studies and our results suggest that the characteristics or context of stimuli can affect spatiotemporal judgments. To work towards a more all-embracing account, a proposal could be that a concept of the contextual change model is added to the attentional gate model. That is, we propose that the number of *perceived* changes of an event may be a factor that is more meaningful for timing perception than the actual/physical frequency of stimuli. The number of perceived changes may then also depend on auditory grouping. For example, an auditory sequence with a certain number of sound onsets that is segmented with a different perceived grouping size would lead to different numbers of auditory grouping (i.e., perceived change) of that sequence. We thus suggest that the number of perceived changes is a crucial factor that modulates the pacemaker rate.

Now that we have combined the number of perceived changes, borrowed from the contextual change model, with the pacemaker rate of the attentional gate model there are still open issues regarding the effects of attention. We speculate that in Chapters 3 and 4, attention was more directed to the auditory sequence when the moving object was occluded (as compared to a condition in which the object was visible). When more attention is directed to the auditory input, the role of auditory rhythm can become more important. Indeed, previous studies showed that rhythm can affect the attentional distribution on an ongoing event (McAuley & Fromboluti, 2014). For example, a study by McAuley and Fromboluti (2014) showed that an auditory rhythm can modulate perceived duration of a sound; participants correctly judged durations when the sound took place at a moment that is congruent with the overall rhythm, as compared to the durations of a late or an early oddball sound that was embedded in a regular sequence. That is, a sequence with a regular rhythm can generate an expectation for an event to happen at a specific moment in time (relatively early or late, depending on the speed of the rhythm). Together, these mentioned studies reveal that auditory rhythm can influence attention. We suggest that the heightened attentional influence of auditory rhythm in occlusion events modulate the gate opening in the attentional gate model (which now also depends on the number of perceived changes).

Some future research directions on spatiotemporal judgments

We found that various characteristics of visual and auditory stimuli affect our time related expectations of amodal movements. Regarding the influence of sound we always used regular, repeating, rhythms. It would be interesting to see how different rhythms or irregular sound sequences would modulate perceived durations. For example, in a study of Horr, Wimber, and Di Luca (2016), participants judged regular sequences to last longer than irregular sequence in a forced choice task. So, we could also investigate spatiotemporal judgments with regular versus irregular sequences. We may question whether irregular sequences affect TTC or judged distance of expected visual movements differently, as compared to the regular sequences (using the same number of sound onsets that we have been investigating).

Besides the effect of stimuli in a different modality, the properties of visual stimuli are still very interesting, particularly regarding the influence of knowledge. For example, we suggested in Chapter 3 that knowledge about friction may affect temporal judgments of a horizontally moving object. Given this, it can be questioned whether perceived duration is easy to be manipulated or whether the modulation of perceived duration is a rather robust finding, depending on just a few variables. A potential future direction of visual influence is to vary properties of visual movements (e.g., a rough surface of an object or background should lead to slower perceived moving speed than a smooth surface of an object or background). Other manipulations could be related to the layout of the visual display. For example, in a pilot study we have investigated the effect of static visual directional symbols superimposed on the occluder (see Figure 5.1 for an example of a trial). The directional symbols could be in the same or opposite direction, or be neutral (i.e., no directional symbol) with the direction of a moving object. We found no effect of such modulations on time to contact judgments. As a follow up on this, displays with dynamic directional cues could be used.

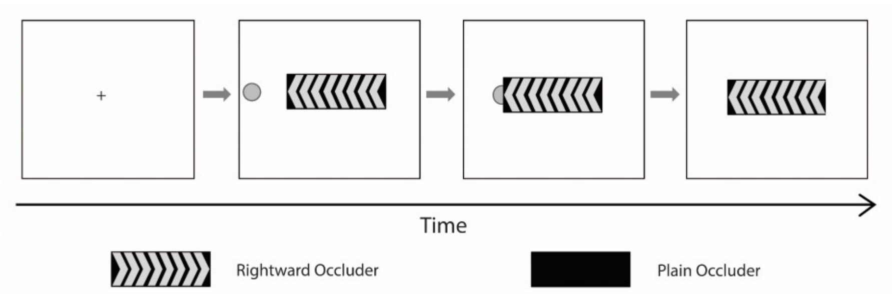

Figure 5.1. A schematic representation of an example trial. The example shows a trial of a leftward directional occluder, and below the timeline, schematic pictures of the rightward directional occluder and the plain occluder (i.e., a neutral condition) are shown.

We also ran a pilot experiment to explore whether spatial compatibility of movement direction and hand response can affect TTC judgments of amodal movements (see Figure 5.2 as an example of the paradigm). Michaels (1988)

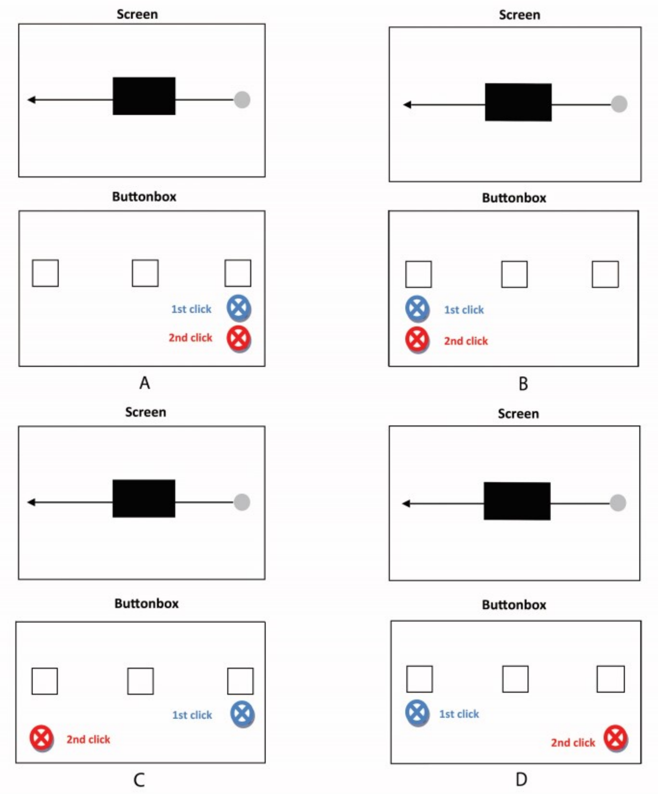

Figure 5.2. Visual stimuli, hand response patterns and block design in a pilot experiment. The schematic diagrams show a disk that moves (here in the leftward direction). The first click initiates a disk to move (shown as a blue circle with a cross inside) and the second click is the judged moment of reappearance (shown as a red circle with a cross inside). There were four blocks: clicking only the right button (Block A), clicking only the left button (Block B), clicking the first button that is located on the side that the disk departs from and clicking the second button that is located on the side that the disk would reappear (Block C), and finally, clicking the first button opposite to the side the disk departs from and clicking the second button opposite to the side the disk would reappear (Block D).

found that compatible responses i.e., straightforward or oblique movements towards the response hand (e.g., an object moved toward the right hand and a right hand response was required) were faster than incompatible responses. This spatial compatibility is defined as ‘stimulus-response (S-R) compatibility’ by Fitts and Seeger (1953). Again, in a pilot experiment (n=11), we found no effect of the spatial congruency between the movement direction of a moving object and the side of hand response when comparing TTC judgments of congruent responses with TTC judgments of incongruent responses or control conditions.

In a follow up, it would be interesting to study the stimulus-response (S-R) compatibility effects on amodal movements using a motor task in more realistic situations like catching or hitting an approaching object in virtual reality settings. When we are more actively involved, the effects may be stronger. In such more realistic situations, also concurrent distractors from the same or the other modalities (e.g., auditory rhythms) may have stronger influences on spatiotemporal judgments.

So far, the message is that the perception of time durations is sensitive to various influences, both unimodal and crossmodal. The influences depend on specific stimulus characteristics, some of which are studied in this thesis. Beside stimulus characteristics also the experimental setting and method play role. With that, time perception appears to be rather flexible and in fact reveals the same basic ambiguity that is inherent to all our perceptions.

Summary

The goal of this thesis was to get a better understanding of unimodal and cross-modal influences on spatiotemporal judgments of occluded motion. In the following, we summarize the main findings for each of the chapters.

In Chapter 2, we investigated whether the perceived duration of an occluded moving object differed from the perceived duration of a visible moving object, under similar conditions. In the first experiment, we found that the perceived motion duration of an occluded moving object was judged to be shorter than the perceived motion duration of a visible moving object. Some previous studies showed that during occlusion eye movements might be different. That is, when an object disappears behind an occluder the eyes often make a saccade to the other edge of the occluder where the object would reappear (S. P. Johnson et al., 2003; Rosander & von Hofsten, 2004; van der Meer, 1994). It was also known that saccades may lead to perceived time compression (Morrone et al., 2005). We therefore performed a second experiment in which we gave participants two different eye movement instructions, as follows. In the 'pursuit condition' the participants were asked to track the moving object with their eyes as accurate as possible, both when the object moved behind the occluder, and when the object moved in front of the occluder. In the 'saccade condition' the participants were instructed to make a saccade to the other side of the occluder at the moment the moving object touched the occluder, again for both conditions, i.e., when the object would move behind the occluder and when the object would move in front of the occluder. We found that the eye movement instructions (i.e., pursuit vs saccade) affected temporal judgment. Particularly, time compression was found when participants were instructed to make a saccade to the other side of the occluder, as compared to pursuit instructions. The visibility of the object (i.e., whether the object passed behind or in front of the occluder) had a more subtle effect on perceived duration and depended on the eye movement instructions.

In Chapter 3, we explored cross-modal effects of auditory rhythms on the perceived duration of occluded motion. We investigated temporal judgments of

amodal movements in a multimodal setting and found that judged time to contact (i.e., judged moment of reappearance) of an occluded moving object can be modified by the rhythm of an accompanying sound sequence. We defined rhythm as an alternation of simple sounds (beeps) and pauses. In Experiments 1 and 2, we found that a relatively fast rhythmic sequence led to an earlier judged reappearance than a relatively slow rhythmic sequence. However, in these experiments different rhythms were created by varying the pause durations. In Experiment 3, we also varied sound duration. The results showed that only variation of pause duration exerted influences on judged time to contact of amodal movements, while variation of sound duration did not have such an effect. This finding converged with previous research on auditory grouping (Geiser & Gabrieli, 2013; Handel & Lawson, 1983, Sussman & Gumenyuk, 2005), and showed that especially the length of pause duration affected grouping. Therefore, we performed an additional experiment in which we asked participants to judge the continuity of auditory rhythms in which we varied pause durations and sound durations. The results revealed that the lengthening of pause duration decreased the perceived continuity of sound sequences, whereas the lengthening of sound duration had no effect. We concluded that the auditory grouping and perceived continuity of the accompanying sound sequence caused slower time to contact judgments of an occluded moving object that we found in Experiments 1 and 2.

In Chapter 4, we investigated spatial judgments of occluded motion in a multimodal setting. In Experiment 1, as with the time to contact judgments in Chapter 3, we found that an accompanying fast rhythmic sequence led to longer judged distance of an occluded moving object than a slow rhythmic sequence. However, this time there was a modulating effect for both pause and sound variations. These results of longer judged distance might be brought about by the higher number of sound onsets of the relatively fast rhythms as compared to the relatively slow rhythms. To determine whether the higher number of sound onsets was crucial or the characteristics of the rhythm, we performed another experiment. In Experiment 2, we varied the number of sound onsets by varying base duration of pause-sound sequences. That is, we created different auditory densities with same auditory rhythm. We then again tested the effect of the auditory sequences on the judged distance of occluded motion. We found that the auditory density was not the main cause of variation of spatial judgments, but that rhythm was the dominant factor. Still, the auditory density had a subtle effect on judged distance of amodal movements depending on speeds of a moving object as we discussed in Chapter 4.

In this thesis, we explored how humans perceive and estimate duration and distance, with regard to unimodal and cross-modal influences. We found that time compression in amodal movement (as in the tunnel effect) is likely to be caused by saccades. Furthermore, not only the characteristics of stimuli from the same modality (e.g., visual speed), but also auditory stimuli (e.g., rhythmic sequences) that are concurrently presented can crossmodally interfere with spatiotemporal judgments of an expected visual event. People seem to automatically combine visual and auditory information that are (near) simultaneously presented, which influences extrapolation of occluded motion. The cross-modal integration of information from visual and auditory modalities appears to be influenced by both the bottom-up (e.g., speed of auditory rhythm) and top-down (e.g., attention) aspects. Such cross-modal influences show that human brains perceive movements in a dynamic fashion, relate information in the surroundings together, and use them to deal with spatiotemporal judgments, also when motion is temporarily occluded.

Nederlandse Samenvatting

Het doel van dit proefschrift was een beter idee te krijgen van unimodale en crossmodale invloeden op de tijdruimtelijke beoordeling van geoccludeerde bewegingen, bewegingen die (deels) geoccludeerd zijn door een ander object. Hier volgt een samenvatting van de belangrijkste bevindingen van ieder hoofdstuk.

In Hoofdstuk 2 onderzochten wij of de waargenomen duur van een geoccludeerd bewegend object verschilt van de waargenomen duur van een volledig zichtbaar bewegend object, onder vergelijkbare omstandigheden. In het eerste experiment vonden wij dat de waargenomen bewegingsduur van een geoccludeerd object als korter wordt ervaren dan de waargenomen bewegingsduur van een volledig zichtbaar bewegend object. Enkele eerdere studies lieten zien dat oogbewegingen tijdens occlusie mogelijk anders zijn dan tijdens het volgen van een zichtbaar object. Anders gezegd, wanneer een object verdwijnt achter een ander object, dan maken de ogen vaak een saccade naar de kant van het occluderende object waar het bewegende object uiteindelijk weer zal verschijnen (S. P. Johnson et al., 2003; Rosander & von Hofsten, 2004; van der Meer, 1994). Ook was al bekend dat saccades kunnen leiden tot perceptuele tijdscompressie (Morrone et al., 2005). Daarom voerden wij een tweede experiment uit waarin we de proefpersonen twee verschillende oogbewegingsinstructies gaven, als volgt. In de 'pursuit conditie' dienden de proefpersonen het bewegende object zo goed mogelijk te volgen met de ogen, zowel wanneer het object achter het occluderende object verdween als wanneer het er voorlangs bewoog. In de 'saccade conditie' dienden de proefpersonen een saccade te maken naar de andere kant van de occluder op het moment dat het bewegende object de occluder raakte, ook weer voor beide occlusie condities, namelijk zowel wanneer het object achter het occluderende object verdween als wanneer het er voorlangs bewoog.

Wij vonden een hoofdeffect voor oogbewegingsinstructie. Met andere woorden, de instructie voor de oogbeweging (pursuit versus saccade) had invloed op de inschatting van de bewegingsduur. Er trad vooral tijdscompressie op wanneer proefpersonen de instructie kregen een saccade te maken naar de andere kant van het occluderende object, in vergelijking met de pursuit instructie. Er bleek echter geen hoofdeffect te zijn van de factor zichtbaarheid. De zichtbaarheid van het object (d.w.z., of het object voor of achter het occluderende object langs bewoog) had een subtiel effect op de waargenomen tijdsduur en was afhankelijk van de oogbewegingsinstructie.

In Hoofdstuk 3 keken wij naar de cross-modale effecten van auditieve ritmes op de waargenomen tijdsduur van geoccludeerde bewegingen. We onderzochten de tijdsschatting van amodale bewegingen in een multimodale setting en vonden dat de geschatte tijd tot verschijning (d.w.z., het geschatte moment waarop het geoccludeerde object weer tevoorschijn kwam) van een geoccludeerd bewegend object veranderd kan worden door het ritme van een begeleidende geluidssequentie. We definieerden een ritme als een afwisseling van simpele geluiden (piepjes) en pauzes. In Experiment 1 en 2 ontdekten we dat een relatief snelle ritmische sequentie leidde tot een vroegere inschatting van het tijdstip waarop het object weer zou verschijnen dan een relatief langzame ritmische sequentie. In deze experimenten werden de verschillende ritmes gecreëerd door de lengte van de pauzes te variëren. In Experiment 3 lieten we ook de lengte van de piepjes variëren. De resultaten lieten zien dat alleen het variëren van de pauzelengte invloed had op de geschatte tijd tot verschijning van amodale bewegingen, terwijl het variëren van de lengte van de geluiden geen dergelijk effect had. Deze bevindingen convergeerden met eerder onderzoek naar auditieve groepering (Geiser & Gabrieli, 2013; Handel & Lawson, 1983, Sussman & Gumenyuk, 2005), en toonden aan dat vooral de lengte van pauzes deze groepering beïnvloedt. Om dit te verifieren voerden wij nog een experiment uit waarin we proefpersonen vroegen de continuïteit van een auditief ritme te beoordelen, waarbij we de lengte van de pauzes en van de geluiden varieerden. De resultaten lieten zien dat langere pauzes de waargenomen continuïteit van geluidssequenties verminderden, terwijl het verlengen van de piepjes geen effect had. We concludeerden dat de auditieve groepering en waargenomen continuïteit van de begeleidende geluidssequentie de oorzaak waren van de langere inschatting van tijd tot verschijning van een geoccludeerd bewegend object dat we vonden in Experiment 1 en 2.

In Hoofdstuk 4 onderzochten we de ruimtelijke inschatting van geoccludeerde bewegingen in een multimodale setting. In Experiment 1 vonden we dat, net als met de inschatting van tijd tot verschijning in Hoofdstuk 3, het aanbieden van een snelle ritmische sequentie zorgde voor een langere inschatting van de afgelegde afstand van een geoccludeerd bewegend object dan het aanbieden van een langzame ritmische sequentie. In dit geval was er echter een modulerend effect van variaties in zowel pauzeduur als geluidsduur. De langere ingeschatte afstand zou kunnen zijn veroorzaakt door het grotere aantal piepjes van de relatief snelle ritmes vergeleken met de relatief langzame ritmes. Om te bepalen of het aantal piepjes de bepalende factor was of de eigenschappen van het ritme zelf, voerden wij nog een experiment uit. In Experiment 2 varieerden we het aantal piepjes door de basisduur van pauze-geluidsequenties te variëren. Dat wil zeggen, we creëerden verschillende auditieve dichtheden met hetzelfde auditieve ritme. Vervolgens testten we opnieuw het effect van de auditieve sequenties op de inschatting van de afgelegde afstand van geoccludeerde beweging. We vonden dat de auditieve dichtheid niet de hoofdoorzaak was van variatie in de ruimtelijke inschatting, maar dat ritme de bepalende factor was. De auditieve dichtheid had echter wel een subtiel effect op de ingeschatte afstand van amodale beweging, afhankelijk van de snelheid van het bewegende object, zoals besproken in Hoofdstuk 4.

In dit proefschrift onderzochten we hoe mensen tijdsduur en afgelegde afstand waarnemen en inschatten met betrekking tot unimodale en crossmodale invloeden. We concludeerden dat tijdscompressie in amodale beweging (net als in het tunneleffect) waarschijnlijk wordt veroorzaakt door saccades. Daarnaast kunnen niet alleen stimuluskarakteristieken van dezelfde modaliteit (bijv. visuele snelheid) maar ook auditieve stimuli (bijv. ritmische sequenties) die tegelijkertijd worden gepresenteerd crossmodaal interfereren met tijdruimtelijke inschattingen van een onverwachte visuele gebeurtenis. Men lijkt visuele en auditieve informatie die (vrijwel) tegelijk worden gepresenteerd automatisch te combineren, wat invloed heeft op de extrapolatie van geoccludeerde beweging. De crossmodale integratie van informatie van visuele en auditieve modaliteiten lijkt beïnvloed te worden door zowel bottom-up (bijv. de snelheid van het auditieve ritme) als top-down (bijv. aandacht) aspecten. Dergelijke crossmodale invloeden laten zien dat het menselijke brein bewegingen op een dynamische manier waarneemt, informatie uit de omgeving combineert, en deze gebruikt bij het maken van tijdruimtelijke inschattingen, ook wanneer beweging tijdelijk geoccludeerd is.

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Curriculum Vitae

My name is Chayada Chotsrisuparat. I was born on November 22, 1985, in Nakhon Pathom Province, Thailand. I received a Development and Promotion of Science and Technology Talents Project (DPST) scholarship from the Royal Thai Government since I have been started my high school at Prapathom Wittayalai School. I then got my Bachelor of Science degree in Biology from Silpakorn University's Sanam Chandra Palace Campus. Later, I received a grant from the Commission on Higher Education. The grant was from the 'Strategic Scholarships for Frontier Research Network' program to pursue a Neuroscience Master Degree at Vrije Universiteit Amsterdam (VU University Amsterdam). After discovering that I was interested in visual motion and time perception, I decided to pursue my PhD at the Donders Institute for Brain, Cognition and Behaviour at Radboud University Nijmegen. I started my PhD in 2012 under the supervision of Dr. Rob van Lier.

Publications

- Chotsrisuparat, C., Koning, A., Jacobs, R., & van Lier, R. (2017). Auditory rhythms influence judged time to contact of an occluded moving object. Multisensory Research, 30(7-8), 717-738.
- Chotsrisuparat, C., Koning, A., Jacobs, R., & van Lier, R. (2018). Effects of auditory patterns on judged displacements of an occluded moving object. Multisensory Research, 31(7), 623-643.

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- Chotsrisuparat C., Koning A., & van Lier R. (2013). Saccades cause compression of time perception in the tunnel effect. 36th European Conference on Visual Perception (ECVP) 2013, Bremen. Perception, 42(1_suppl), 181. doi:10.1177/03010066130420S101.

- Chotsrisuparat, C., Koning A., & van Lier R. (2014). Auditory rhythms influence perceived time durations of a tunnelling object. 37th European Conference on Visual Perception (ECVP) 2014, Belgrade. Perception, 43(1_suppl), 149. doi: 10.1177/03010066140430S101.

- Chotsrisuparat, C., Koning A., & van Lier R. (2015). Auditory rhythms influence perceived distance of an occluded moving object. 38th European Conference on Visual Perception (ECVP) 2015, Liverpool. Perception, 44(1_suppl), 239. doi:10.1177/0301006615598674.

Conference presentations

- Donders Discussion 2013, Nijmegen. Chotsrisuparat, C., Koning A., & van Lier R. Saccades cause compression of time perception in the tunnel effect.

- Perception Day 2013, TU Eindhoven. Chotsrisuparat, C., Koning A., & van Lier R. Saccades cause compression of time perception in the tunnel effect.

- Speaker at Perception Day 2014, 7th November 2014, TU Eindhoven. Chotsrisuparat, C., Koning, A., & van Lier, R. Auditory rhythms influence perceived time durations of a tunnelling object.

- Donders Discussion 2014, Nijmegen. Chotsrisuparat, C., Koning A., & van Lier R. Auditory rhythms influence perceived time durations of a tunnelling object.

Donders Graduate School for Cognitive Neuroscience

For a successful research Institute, it is vital to train the next generation of young scientists. To achieve this goal, the Donders Institute for Brain, Cognition and Behaviour established the Donders Graduate School for Cognitive Neuroscience (DGCN), which was officially recognised as a national graduate school in 2009. The Graduate School covers training at both Master's and PhD level and provides an excellent educational context fully aligned with the research programme of the Donders Institute.

The school successfully attracts highly talented national and international students in biology, physics, psycholinguistics, psychology, behavioral science, medicine and related disciplines. Selective admission and assessment centers guarantee the enrolment of the best and most motivated students.

The DGCN tracks the career of PhD graduates carefully. More than 50% of PhD alumni show a continuation in academia with postdoc positions at top institutes worldwide, e.g. Stanford University, University of Oxford, University of Cambridge, UCL London, MPI Leipzig, Hanyang University in South Korea, NTNU Norway, University of Illinois, North Western University, Northeastern University in Boston, ETH Zürich, University of Vienna etc. Positions outside academia spread among the following sectors:

-specialists in a medical environment, mainly in genetics, geriatrics, psychiatry and neurology,

-specialists in a psychological environment, e.g. as specialist in neuropsychology, psychological diagnostics or therapy,

-higher education as coordinators or lecturers.

A smaller percentage enters business as research consultants, analysts or head of research and development. Fewer graduates stay in a research environment as lab coordinators, technical support or policy advisors. Upcoming possibilities are positions in the IT sector and management position in pharmaceutical industry. In general, the PhDs graduates almost invariably continue with high-quality positions that play an important role in our knowledge economy.

For more information on the DGCN as well as past and upcoming defenses please visit: http://www.ru.nl/donders/graduate-school/phd/.